

## Review

## How scale and technology influence the energy intensity of water recycling systems-An analytical review

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## ABSTRACT

Many cities are moving towards increased use of recycled water to meet water demand due to freshwater scarcity, population growth, urbanisation and climate change. Water recycling requires substantial energy. Water utilities are facing serious challenges providing cost-effective and reliable water services under rising energy cost. Energy is further linked with global climate change through carbon intensive Greenhouse Gases (GHGs) emissions. However, few studies have attempted to understand the energy use of water recycling systems and how energy intensity of those systems varies with scale and technology. In this paper, we undertook a comprehensive and systematic literature and data review to understand the energy intensity of water recycling systems. We used four "cases": (1) Centralised Potable (2) Centralised Non-Potable, (3) Decentralised Potable and (4) Decentralised Non-Potable systems to structure our work. Our analysis demonstrates how energy intensity of water recycling systems decreases with increasing size for a wide range of scale and for different treatment technologies. The treatment energy intensity for centralised systems having capacity less than 5 MLD varies from 0.48 to 2.0 kWh/kL for non-potable and 0.75 to 2.0 kWh/k for potable; for capacities between 5 and 200 MLD varies from 0.2 to 0.9 kWh/kL for potable and from 0.25 to 0.75 kWh/kL for non-potable; and for any capacity greater than 200 MLD, the treatment energy intensity is less than 0.8 kWh/kL for potable and 0.55 kWh/kL for non-potable systems. But current centralised water recycling systems have a treatment energy intensity from 0.65 to 1.4 kWh/kL for Potable for capacity from 21 to 378 MLD and from 0.6 to 1.0 kWh/kL for non-potable systems for 6 to 350 MLD. In the case of decentralised systems, smaller systems consume higher energy than centralised systems but larger decentralised Systems (mid-size) have lower energy intensity. Though the treatment energy intensity of a centralised system is low, the reuse of treated water for non-potable water requires a dual pipe system which involves a good amount of pumping energy due to the long distance between the treatment plant and the users. Pumping energy, in this case, can vary from 0.19 to 1.43 kWh/kL. The selected treatment technology and train have also influence on the energy use. The present trend of water recycling is to produce high-quality recycled water for all non-potable reuse using Advanced Water Treatment but all non-potable water uses do not necessarily require such high quality water. Little attention has been given to introducing 'fit for purpose' water reuse using appropriate technologies and larger decentralised (distributed) water recycling systems that have the potential to reduce energy intensity for cost-effective urban water services.

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## 1. Introduction

Energy is a critical parameter in designing sustainable water service systems<sup>1</sup> (Rygaard et al., 2011; Dreizin, 2006) as energy is a significant contributor to the total cost for water services (Schwarzenegger, 2005; Navigant Consulting Inc. 2006; Dreizin, 2006; Kenway et al., 2008; Rygaard et al., 2011; Copeland, 2014). It is a considerable challenge for water utilities to provide cost-effective water services given recent increases in the energy price (Rygaard et al., 2011; Cook et al., 2012; Copeland, 2014). Concerns about climate change are also promoting local, state, and federal agencies to identify the most effective and efficient ways of reducing energy use and greenhouse gas emissions (CSA, 2008). Some agencies are voluntarily setting emissions reduction targets in response to growing concern about the potential impacts of climate change on water resources (CSA, 2008; Kenway et al., 2008; Kenway et al., 2011).

Producing recycled water requires more energy than typical wastewater treatment to bring it to reuse standard for human consumption and then conveying it back to the users (WRR, 2012; EPRI and WRF, 2013). The demand for energy for water services will further increase due to stringent water quality requirements and treating emerging contaminants in wastewater (ASTE, 2012; Angelakis and Gikas, 2014). Therefore, this will hamper cost-effective water services and contribute to increased GHG emissions (Cook et al., 2012; Angelakis and Gikas, 2014). Water utilities are facing challenges finding ways to reduce the energy consumption for water services. However, few studies have been done on estimating the energy intensity of utility's typical water and wastewater systems from where secondary/tertiary treated water (to meet environmental standards) is also used for non-potable purposes. The first in-depth study was initiated in California by the California Energy Commission (CEC) (Navigant Consulting Inc. 2006; Kenway et al., 2008; Kenway et al., 2011; Kenway, 2013).

This study shows that the water sector is a major user of California's total energy accounting for 19% of the total state electricity use in 2001 (Navigant Consulting Inc. 2006). Potable water services accounted for 3–4% of total electricity (80% for transporting) (Moore, 2012; Navigant Consulting Inc. 2006; Schwarzenegger, 2005). Pumping and aeration in wastewater treatment plants are the largest energy consumers (Moore, 2012; Navigant Consulting Inc. 2006; Schwarzenegger, 2005).

Though energy consumption by water service systems is a small fraction of total electricity as discussed earlier, it has large cost implications on the budget of water utilities. In developed countries, energy is the second highest operation and maintenance cost after labour (Copeland, 2014). Water utilities in developed countries roughly spend 15–30% of their operating budget for energy at large wastewater treatment plants and 30–40% at small wastewater treatment plants (Moore, 2012; Bounds and Denn, 2017). The US EPA estimates that energy expenditure for providing water services in the USA is around \$4 billion annually (US EPA, 2012). Electricity prices have risen in the USA by nearly 20% over the last decade and are expected to continue to rise (IEA, 2010). Stokes and Horvath (2010) state that due to increased demand for water and wastewater services from population growth in Australia, the energy demand for water services could increase by 33% over a period of 20 years. IEA (2014) estimates that energy demand for water sector can increase by half by 2040. Further, Bounds and Denn (2017) report that the energy requirement for wastewater treatment plants with biological treatment for nutrient removal will increase by 20% in next 15 years to meet stringent requirements of Safe Drinking Water Act and the Clean Water Act.

In developing countries, the energy cost for water services in many cases is higher than 40% and can be as high as 70% as is the case of Bangalore city (IBM, 2010; CSE, 2011). The rising energy prices and the pursuit of more energy-intensive water alternatives will increase energy costs dramatically and larger percentage of utilities' expenditures (ASTE, 2012; IEA, 2018; Cook et al., 2012; Marks, 2007). This will hamper cost-effective water services (IEA,

<sup>1</sup> Water service means water supply and sewerage/sanitation.

2018; Daigger, 2009; Cook et al., 2012). It is the mandate of water utilities to protect public health and environment and provide water services at an affordable price (Copeland, 2014). Therefore, it is imperative that urban water utilities finding appropriate measures to reduce energy use in wastewater/water recycling systems.

Recycled water use has been a part of water management strategies and an innovative means in water-stressed and growing cities to reduce the growing urban water scarcity (Apostolidis et al., 2011; ASTE, 2013; ISF, 2013; Angelakis and Gikas, 2014; WRRF, 2015; EU, 2016; PUB, 2016; Mukheibir and Currie, 2016; Watson, 2017). Many countries around the world have also set their targets for increased recycled water use (EU, 2016; NSW Office of Water, 2010; CSIRO, 2009; CSA, 2008; ACT Health, 2007; Miller, 2006; Radcliffe, 2006). In the EU, especially those in water-stressed regions, about 30% of total water use is currently met by recycled water. In the USA, the use of treated wastewater is less than 5% of municipal water supplies (Grant et al., 2012). The current target of the USA is to increase recycled water use by 58% in the next 10 years (Water Online, 2016 and WaterReuse, 2018). Singapore meets more than 18% of urban water demand and 32% of industrial water needs from recycled water. The future target is to meet 50% of urban water demand from recycled water by 2060 (Angelakis and Gikas, 2014). As a response to the millennium drought, Australia expanded recycled water use from 17% to 20% in 2009–2010 and to 25% by 2015 (ASTE, 2004). Australia has set a target of 30% of urban water demand to be met from recycled water by 2030 (State Water Plan, 2007; Kenway et al., 2008; ERA, 2009; Kenway et al., 2011; Cook et al., 2012).

Recycled water from wastewater can be produced using centralised and decentralised systems. In developed countries, recycled water is usually produced using centralised systems. Producing recycled water through centralised systems may not require substantial energy, as they treat wastewater up to a secondary or tertiary level to meet the environmental requirement (Cooley and Wilkinson, 2012; CSA, 2008). However, pumping the treated water back to users is energy intensive due to the long distance between users and a water recycling system (ASTE, 2004; CSA, 2008; Daigger, 2009; Kenway et al., 2008; Cook et al., 2012; ISF, 2013b). One of the drivers of energy use to recycling water through the centralised system is the level of wastewater treatment but in most centralised systems, wastewater is treated up to secondary level (CSA, 2008). Developing countries have pioneered the use of decentralised wastewater treatment systems to protect their environment due to low sewerage coverage and in many cases, they have now started using the treated water for different non-potable water applications. Some developed countries, especially water-stressed countries such as Australia, USA, Japan and China have also implemented decentralised water recycling systems to meet urban water demand and protect the environment (CSA, 2008; Mitchell et al., 2008; ISF, 2013).

In between large centralised systems and lot scale/small-scale decentralised systems, medium sized systems known as distributed water recycling systems (including sewer mining) have attracted much attention recently. Australia has pioneered distributed water recycling systems (Biggs et al., 2009; ISF, 2013; ISF, 2013a; Mitchell et al., 2008; Watson et al., 2017) and other countries are following similar approaches (Thippeswamy, 2018; Kumar, 2013; Ravindra, 2012).

Limited studies have been done to understand energy intensity<sup>2</sup> of water recycling systems (CSA, 2008; EPRI and WRF, 2013;

Kavvada et al., 2016; Cooley and Wilkinson, 2012; Sharma et al., 2012; Cook et al., 2012; ISF, 2013; ISF, 2013a). Further, there is no comprehensive literature review on how different scales or systems influence energy use. Studies on the energy intensity of wastewater treatment systems/water recycling systems have been concentrated particularly in Australia and the USA (Schwarzenegger, 2005; Navigant Consulting Inc. 2006; CSA, 2008; Kenway et al., 2008; Grant et al., 2012; Cooley and Wilkinson, 2012; Shehabi et al., 2012; WRRF, 2012; Sharma et al., 2012; Lane et al., 2012; ISF, 2013; Angelakis and Gikas, 2014; Lafforgue and Lenouvel, 2015; Kavvada et al., 2016; Verstraete and Vlaeminck, 2011). In developing countries, consideration of energy use for water services is not a priority as their main thrust is to meet 100% water supply at any cost. Therefore, little information is available.

Another factor that affects the energy intensity of water recycling system is the level of treatment required for various end uses. The selection or use of a technology has, therefore, influence on energy use in wastewater/water recycling systems. The secondary treated water from centralised systems that uses traditional Activated Sludge or Trickling Filter/aerobic treatment can be used for much non-potable water uses such as irrigation, toilet flushing, commercial and industrial uses where human contact is not involved (Crook et al., 2005; Angelakis and Gikas, 2014). Secondary treatment is done using mechanical treatments example for Conventional Activated Sludge (CAS) and Trickling Filter (TF) and are very popular (CSA, 2008). However, some countries particularly developing countries where sufficient land is available, prefer natural treatment processes such as lagoons and stabilization ponds because of their low cost and ease of operation (Behrends, 2009).

Tertiary treated water is used for non-potable reuse where human contact is involved such as washing lawns, gardening and other uses (Crook et al., 2005; Angelakis and Gikas, 2014). Tertiary treatment is done through filtration of secondary treated water using media or membranes such as membrane-bioreactors (MBR) followed by disinfection (Crook et al., 2005).

High quality purified/potable water<sup>3</sup> for drinking is now possible using Advanced Water Treatment (AWT) technologies<sup>4</sup> and following a multi-barrier protection against trace organic matters. DPR is yet rare, Namibia is the first, longest and successful use of DPR, but some water-stressed countries such as the USA and South Africa have implemented or undertaken several projects recently and Australia is also working on how to use DPR (Tchobanoglous, 2013; WRRF, 2015; WR California, 2014; Water Online, 2016; WRRF, 2012; Price et al., 2010). However, Indirect Potable Reuse (IPR) and Non-potable water reuse using centralised water recycling systems are common particularly in water-stressed countries (Hall et al., 2009; Tchobanoglous, 2013; WR California, 2014; WRRF, 2015; Tchobanoglous, 2015).

Thousands of water recycling systems have been implemented globally using both centralised and decentralised systems for both potable and non-potable urban uses. However, there is no comprehensive review of how different technologies influence energy intensity to produce potable and non-potable water. Similarly few studies have focussed on how desired water quality or 'Fit for purpose' recycled water is being followed to reduce energy use in water recycling systems (Zhang et al., 2013; Navigant Consulting Inc. 2006; Rygaard et al., 2011; CSA, 2008; Hall et al., 2009; Grant

<sup>2</sup> Energy intensity is the relative amount of energy needed to perform water management-related tasks such as treating and pumping water or for the whole water use cycle. It is typically expressed as the number of kilowatt-hours per million gallons of water (Navigant Consulting Inc. 2006; Copeland 2014).

<sup>3</sup> Recycled water for potable use can be done either directly called 'Direct Potable Reuse (DPR)' by feeding it into water reservoir before distribution or water distribution network or indirectly using surface water or groundwater as buffer called 'Indirect Potable Reuse' (IPR).

<sup>4</sup> AWT technologies include membrane treatment, particularly reverse osmosis (RO) or Nano-filtration, chemical precipitation, carbon absorption, ion exchange, Biological Nutrient Removal and advanced oxidation processes such as UV or H<sub>2</sub>O<sub>2</sub>.

et al., 2012; Verrecht et al., 2010; PUB, 2011; Cooley and Wilkinson, 2012; EPRI; WRF, 2013; Sharma et al., 2012; Pellegrin and Kinnear, 2012).

In this article, we, therefore, make a comprehensive and systematic review of existing literature and data available with attention to the effect of scale and technology influence on the energy-intensity of water recycling systems.

## 2. Methodology

The energy intensity of water recycling systems depends on multiple factors such as the scale of economies, treatment technologies, purposes of end uses, influent wastewater characteristics, regulations/discharge permits, standards for recycled water quality and pumping requirement (CSA, 2008; Kenway et al., 2008; Bounds and Denn, 2017). Producing high-quality water require advanced technologies especially for drinking. However, much non-potable water use such as toilet flushing, gardening, firefighting, and construction purpose can be met with lower quality water and can be produced with less energy. Such uses do not necessarily require high-quality drinking water. We, therefore, consider here four “cases” shown in Figure-1 that have the potential to reduce the energy intensity of water recycling systems for urban water services. We use these four cases to review the existing literature how those have been followed thus far to produce recycled water and its reuse.

Estimating the energy intensity of a recycled water system/typical wastewater system is a complicated process and requires a system boundary/water use cycle to follow for a comparison of one with the other (Navigant Consulting Inc. 2006; Kenway et al., 2008; Cooley and Wilkinson, 2012).

The energy intensity of a water recycling system is the energy required per volume of wastewater for the whole process involving collection/conveyance, treatment, and distribution and usually measured as kWh/MG<sup>5</sup> or kWh/kL (m<sup>3</sup>)<sup>6</sup> (Schwarzenegger, 2005; Navigant Consulting Inc. 2006). We consider here that for a centralised recycled water system, the source of raw water is ‘Secondary treated wastewater system’ as in many cases centralised wastewater is treated to secondary treatment standard before its disposal to the environment. However, sometimes the secondary treated wastewater is conveyed to another distant system for recycling where conveyance energy needs to be included. In decentralised water recycling systems, the raw water for a recycled water plant is domestic/commercial/industrial wastewater’ or a combination of these. Therefore, the energy intensity of a decentralised water recycling system is the energy required per volume of water to collect, treat and distribute the recycled water. We have used these system boundaries as shown in Fig. 2 for our literature review and analysis.

Further, for centralised water recycling systems, we have considered municipal wastewater and for decentralised water recycling systems, domestic wastewater. We consider wastewater since it is independent of climate change (Paul et al., 2018).

We have focussed on operational energy in our study as it is often the most significant part of energy consumption in a centralised water and wastewater treatment system (Kavvada et al., 2016; Kenway et al., 2008; Flower et al., 2007). Kavvada et al. (2016), assessed life cycle energy and GHG emissions of centralised and decentralised systems for non-potable reuse. This demonstrated that the embodied energy and GHG emissions for manufacture, construction, operation and maintenance is insignificant. They also note if decentralised systems are made bigger in

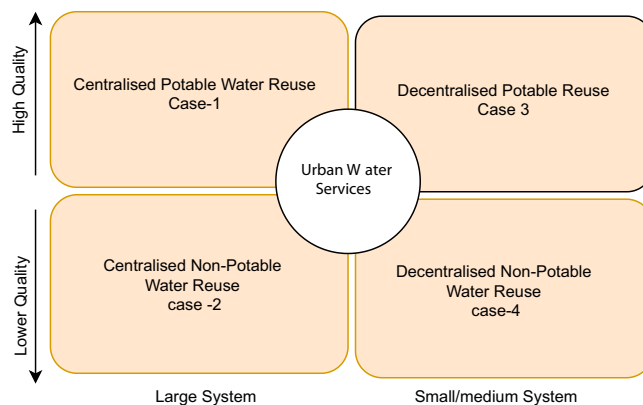


Fig. 1. Four different “Cases” to review the energy intensity of water recycling systems.

scales than smaller ones as practised, those life cycle energy and GHG emissions could be further less. Centralised wastewater treatment systems usually have less lifecycle energy GHGs emissions but Bradshaw and Luthy (2017) recently show that it can be high when more pumping is involved for water reuse. The uncertainty of having low life cycle energy and GHGs emissions for the centralised system is high but for larger decentralised (distributed) systems, the pumping energy can be reduced by choosing the appropriate location of a plant and further a ‘Fit for Purpose’ of recycled water can reduce further energy. Thus for such systems, getting less life-cycle cost is a bit certain. But in all cases, operational energy is the most significant part of energy use. Therefore, we have used this assumption under our scope of work.

We considered a review of conventional wastewater treatment technologies as those are used in decentralised water recycling systems for secondary treatment and secondary/tertiary treated water from centralised systems in many cases are used for non-potable purposes.

## 3. Water recycling systems and water reuse

### 3.1. Centralised water recycling systems and water reuse

The large-scale unintended water reuse projects started in Central Europe for agriculture during 1500–1800 BC through the use of partially treated wastewater from the conventional/centralised wastewater treatment system started back to Minoan Civilization before 3500 BC (Angelakis and Gikas, 2014). The intended water reuse projects were implemented in California in the 19th Century (Crites and Tchobanoglous, 1998; Tzanakakis et al., 2007; Angelakis and Gikas, 2014). The economic and environmental benefits of the intended use of recycled water in crop yield in California motivated the expansion of water reuse worldwide. Understanding the health risk of wastewater, the State of California first issued regulations in 1918 governing water recycling in agriculture (CSBH, 1918).

Currently, over 60 countries around the world are using centralised recycling water systems for different non-potable purposes such as toilet flushing, car washing, landscape irrigation, industries, commercial use, groundwater recharge. In some cases, this has extended to drinking water as direct and indirect potable water reuse (Angelakis and Gikas, 2014; Asano et al., 2007; Gikas and Tchobanoglous, 2010). US EPA has taken initiative to mainstream potable use of recycling water (US EPA, 2018). Fig. 3 shows different ways of water reuse around the world. Recycling water has the highest use for agriculture (32%), landscape irrigation (20%), industrial use (19%), Groundwater recharge (2%) and the remaining 17% for urban use (17%) (EU, 2016).

<sup>5</sup> 1 MG equal 3785.4 kilolitres

<sup>6</sup> kWh (Kilo watt hour), kL-kilolitre.

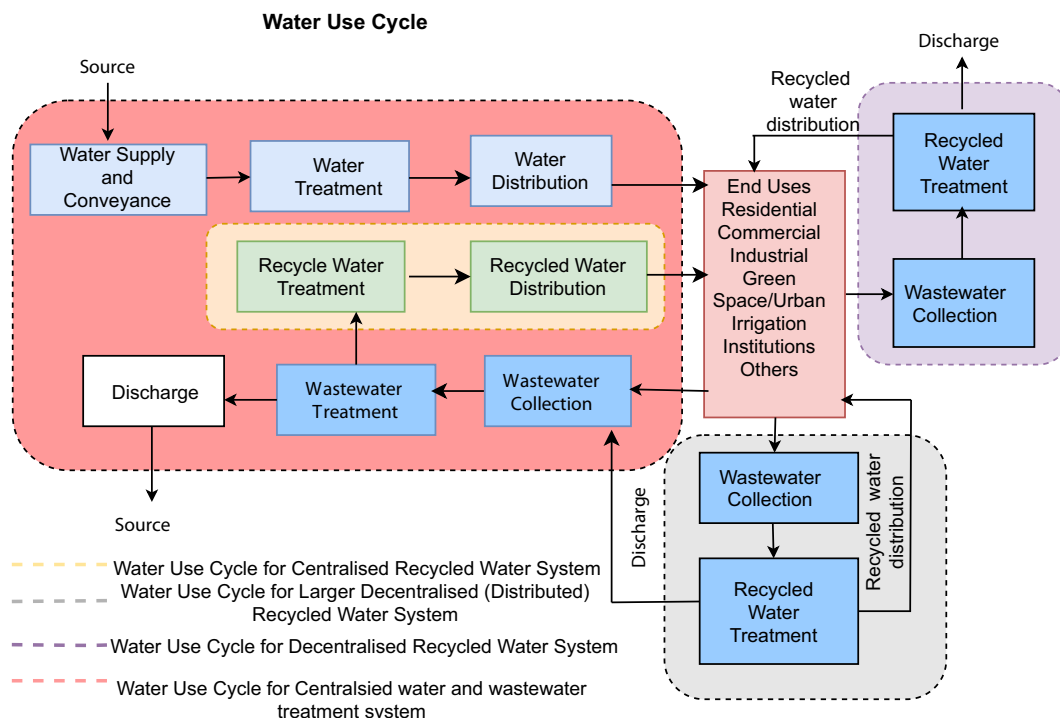


Fig. 2. Water Use Cycle (System boundary) of various water recycling systems.

#### Direct potable reuse (DPR)

Direct Potable Reuse is not common due mainly to people's perception or psychological barrier in relation to the source for the recycled water (Agelakos and Gikas, 2014).

#### Indirect potable reuse (IPR)

Holding the tertiary or advanced treated water for a certain time (or using a buffer) in groundwater or surface water reservoirs is called indirect potable reuse (Grant et al., 2012). IPR has been common in many parts of the world because of the use of long retention of water in the environmental buffer that has the acceptability by the people in most cases (Gerrity et al., 2013).

#### Non-potable water reuse (NPR)

The tertiary treated water or Advanced Treated Water from centralised wastewater plants can be used for non-potable urban uses such as flushing toilets, washing cars, landscape irrigation, commercial and industrial uses. Such uses do not require high-

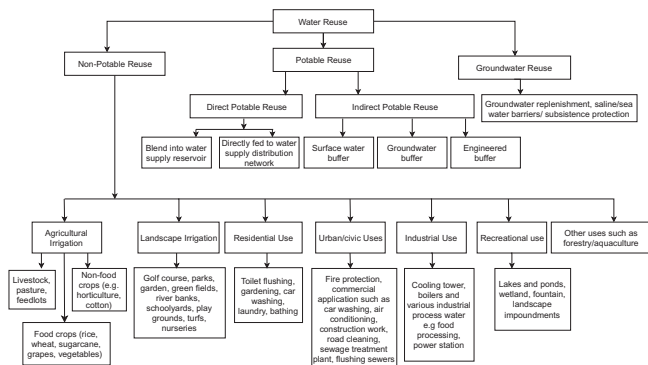


Fig. 3. Different types/Quality recycled water use for various end uses around the world (CSBH, 1918; WHO, 1989; US EPA, 1992; Griffith, 2003; ASTE, 2004; Asano et al., 2007; ASTE, 2012; Chen et al., 2017).

quality water using AWT which can be met with tertiary treated water. For non-potable reuse, it requires a separate distribution network called dual pipe system/network from the potable supply for its distribution to the end users.

The methods (DPR, IPR and NPR) of using recycled water from centralised water and wastewater treatment systems are shown in Fig. 4.

#### 3.2. Decentralised water recycling systems and water reuse

Decentralised water recycling water systems collect, treat and distribute treated water near the point of generation shown in Fig. 5 (Crities and Tchobanoglous, 1998; Daigger, 2009; Masood et al., 2009; Water Online, 2014). They have several advantages such as these can reduce transport/pumping of wastewater collection, conveyance and recycling and thus can reduce both direct and indirect energy (Agelakos and Gikas, 2014; Masood et al., 2009; Nelson, 2011; Kavvada et al., 2016; WRRF, 2015). A decentralised system 1) can be tailored for location-specific solutions 2) avoids costly augmentations to centralised systems and 3) avoids the inherent financial risks for new vast wastewater infrastructure

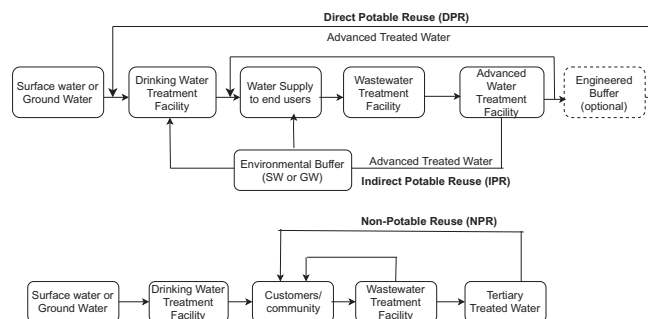


Fig. 4. Centralised Water recycling systems (DPR, IPR, and NPR) (Leverenz and Tchobanoglous, 2011; ASTE, 2013; WR California, 2014).

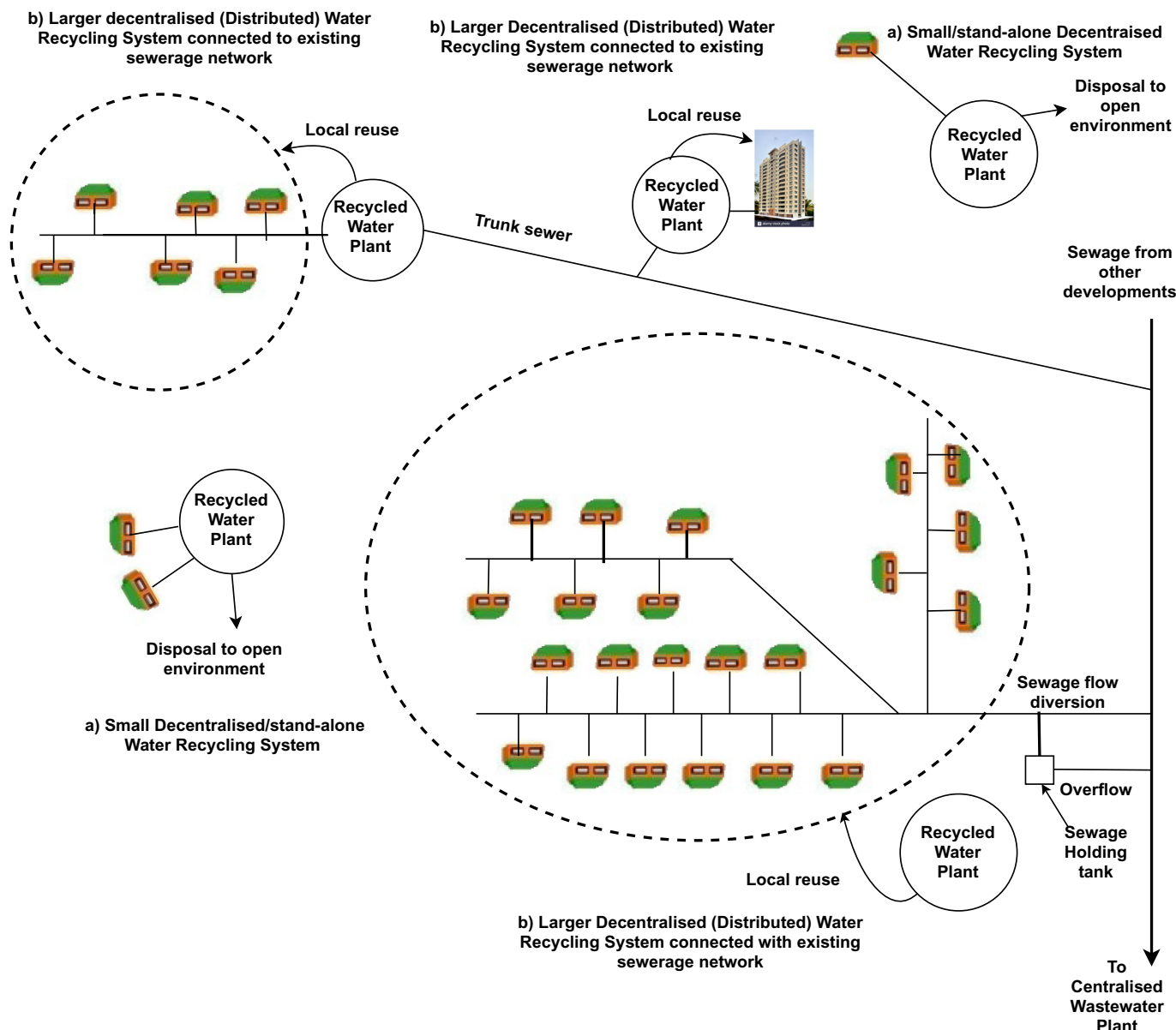


Fig. 5. Decentralised Water recycling systems (adapted from Gikas and Tchobanoglous, 2009; Prieto et al., 2013).

(Tjandraatmadja et al., 2009; Fane et al., 2006; Mitchell et al., 2008; Sharma et al., 2012). Further, decentralised water recycling systems can meet specific water quality requirements of the end-uses, potentially avoiding the need to produce single high-quality water for all purposes, unlike centralised systems which can save energy (Biggs et al., 2009; Kavvada et al., 2016). US EPA guidelines underscore that wastewater utilities can save energy using decentralising treatment facilities as smaller systems can save energy cost of conveyance and fresh water from local reuse (US EPA, 2012).

Decentralised systems are usually practised as a remote community and stand-alone systems with no connection or back up with water grid and are small in scale (Biggs et al., 2009) shown in Fig. 5a. But recently larger (cluster or development scale) decentralised water recycling systems have been pioneered in Australia which is connected or can be connected with an existing sewerage network shown in Fig. 5b. They termed it as 'distributed water

recycling system' - an emerging system or niche like recycled water grid (Mitchell et al., 2008; Gikas and Tchobanoglous, 2008; Cook et al., 2009; Watson, 2011). Gikas and Tchobanoglous (2008) term distributed systems as satellite systems and consider those as an integral part of centralised water and wastewater system (Fig. 5). Such systems follow the basin approach of water management and thus are sustainable and resilient to climate change (Gikas and Tchobanoglous, 2008; Biggs et al., 2009).

Despite various advantages of decentralised water recycling systems, limited studies have been done to understand the energy intensity of both decentralised and distributed systems. The energy intensity of decentralised and distributed water recycling systems have been discussed in section 6.3 and 6.4 and details in Appendix A (Table A4).

#### 4. Influence of regulations/water standards and influent wastewater characteristics on energy intensity of water recycling systems

Regulations play an important role in the level of treatment of wastewater for various end uses. Strict regulations involve higher energy use (Cooley and Wilkinson, 2012). The US EPA prescribes treatment levels/standards for a wide variety of uses in its Guidelines for Water Reuse (US EPA, 2004). The US EPA recommends that recycling water after secondary treatment followed by filtration and disinfection can be used for all urban purposes including toilet flushing, landscape irrigation, car washing. Recycling water after Secondary treatment with disinfection can be safely used for construction and industrial purposes (US EPA, 2004). Only potable reuse (both direct and indirect) require more stringent treatment. The fundamental rule for water reuse is that water reuse applications should not cause unacceptable public health risks.

Some states and countries example for Australia, various states in the USA and EU countries, have set strict and uniform regulations and guidelines for the reuse of treated wastewater for extra protection of health and environment (Apostolidis et al., 2011). But such strict regulations have been very controversial. Angelakis and Gikas (2014) stated that the controlled use of recycled will prevail in the coming future, but water reuse may be discouraged in cases of enforcement of unjustifiable strict water quality standards. It can ultimately affect the expansion of recycling water use because of higher energy use and associated high cost. The recycled water quality for various types and specific uses have been elaborated in Table A.1 in Appendix A.

Variability in energy intensity is largely driven by influent and effluent water quality and the kind of processes employed (ASTE, 2012). The source of water of a water recycling system is 'wastewater'. In a centralised recycled water system, raw water for water recycling system is secondary treated water which usually corresponds to the water quality of BOD<25 mg/l and TSS<35 mg/L irrespective of treatment technologies (Asano and Levine, 1996). Table A.2 in Appendix A shows typical characteristics of domestic wastewater commonly used for decentralised and distributed water recycling system design (Seigrist et al., 2013).

#### 5. Energy intensity of recycled water treatment technologies

The selection of technologies significantly affects energy use in wastewater treatment/water recycling systems. The wastewater treatment can be categorized as a physical, chemical and biological process:

- Physical Process — screening, sedimentation, filtration, centrifugation
- Chemical Process — coagulation, oxidation-reduction, disinfection, ion exchange Biological process-aerobic and anaerobic treatment, oxidation pond/stabilization ponds

Conventional/Municipal wastewater treatment usually involves preliminary, primary, secondary, and disinfection. Tertiary and advanced water treatment is an additional treatment for higher-level removal of some specific pollutants such as nitrogen. Phosphorous, dissolved solids/trace organic matters which cannot be removed using secondary treatment. In developing countries, low-cost technologies such as lagoon and waste stabilization ponds are widely used to remove these specific parameters and such treatment processes are simple and easy to operate. But in developed<sup>7</sup> countries, AWT technologies such as River Osmosis (RO),

Membrane Bioreactor (MBR), Micro Filtration (MF), Ultra Filtration (UF), Nano Filtration (NF) and Advanced Oxidation Technologies (AOT) using H<sub>2</sub>O<sub>2</sub> (hydro peroxide), UV (Ultra Violet), O<sub>3</sub> (Ozone) are commonly used (Grant et al., 2012; Lafforgue and Lenouvel, 2015; Verstraete and Vlaeminck, 2011). Fig. 6 shows different processes for conventional and advanced water or tertiary treatments, their objectives and water reuse points with specified types of end uses from centralised wastewater treatment/water recycling systems.

For decentralised water recycling systems, secondary and tertiary/advanced treatment are followed and the technologies mentioned in Fig. 6 are used for these treatments.

##### 5.1. Conventional wastewater treatment (CWWT) technologies and their energy intensities

Among conventional technologies, Activated Sludge for secondary wastewater treatment is the most common and the oldest technology used since 1904 (Asano and Levine, 1996). The second commonly used technology is Trickling Filter. Both technologies use the aerobic process.

As shown in Table 3, Stillwell et al. (2010) report Conventional Activated Sludge (CAS) Process has an average energy intensity from 0.2 to 1.43 kWh/kL and CAS that uses anaerobic digestion has lower energy consumption (Muga and Mihelcic, 2008). Trickling Filter (TF) involves less energy from 0.18 to 0.48 kWh/kL than CAS to achieve the same quality water. The CAS also involves more energy than lagoon or land treatment but Aerated Lagoons (AL) have higher energy intensity around 1.93 kWh/kL. But TF with attached growth has much less energy, ranging from 0.13 to 0.17 kWh/kL (Stillwell et al., 2010). Oxidation Ditches (OD) have higher energy intensity than CAS (Stillwell et al., 2010; Denn, 2012).

A combination of Trickling Filter and Biological Nutrient Removal (BNR) (advanced treatment) has good treatment capacity and the energy intensity varies from 0.34 kWh/kL to 0.66 kWh/kL. This level of treated water is suitable for non-potable purposes (EPRI and WRF, 2013). Non-potable water reuse at lower energy is also possible using 'Waste stabilization ponds (WSP).<sup>8</sup> Nevertheless, such systems require large amounts of land. This technology is commonly used in the Netherlands and Brazil (Crook et al., 2005). The world's largest WSP system in Melbourne produces 40 GL/yr<sup>9</sup> of treated wastewater that uses approximately 0.33 kWh/kL<sup>10</sup>, 0.5 kWh/kL less energy than the other conventional wastewater treatment in Melbourne. Water from this plant is used for non-potable applications including plantation and agricultural irrigation, golf courses, watering garden and conservative areas (Grant et al., 2012 and Melbourne Water, 2017). The energy intensity of WSPs can vary from 0.33 to 1.2 kWh/kL (Stillwell et al., 2010).

Recently anaerobic-aerobic combined processes have proven to have many advantages such as low energy and chemical consumption, low sludge production, a wide range of potential resource recovery, less equipment and smooth operation. However, this necessitates high retention time (HRT) and ample space and facilities to produce biogas (Chan et al., 2009).

There are limited studies on the energy intensity of various conventional technologies and a combination of technologies or treatment trains (Cooley et al., 2012). A literature review of the

<sup>8</sup> In a WSP, wastewater is allowed through a series of open shallow ponds under air and where physical processes (flocculation and gravitational sedimentation), microbial processes (algal growth, aerobic and anaerobic heterotrophic metabolism, nitrification, and denitrification) and exposed to sunlight for joint removal of pathogens, organic contaminants, and nitrogen.

<sup>9</sup> GL/Yr- Giga litre/Year.

<sup>10</sup> Calculated using the value reported in the Melbourne Water Annual report 2016-2017.

<sup>7</sup> Countries as defined by the World Bank.

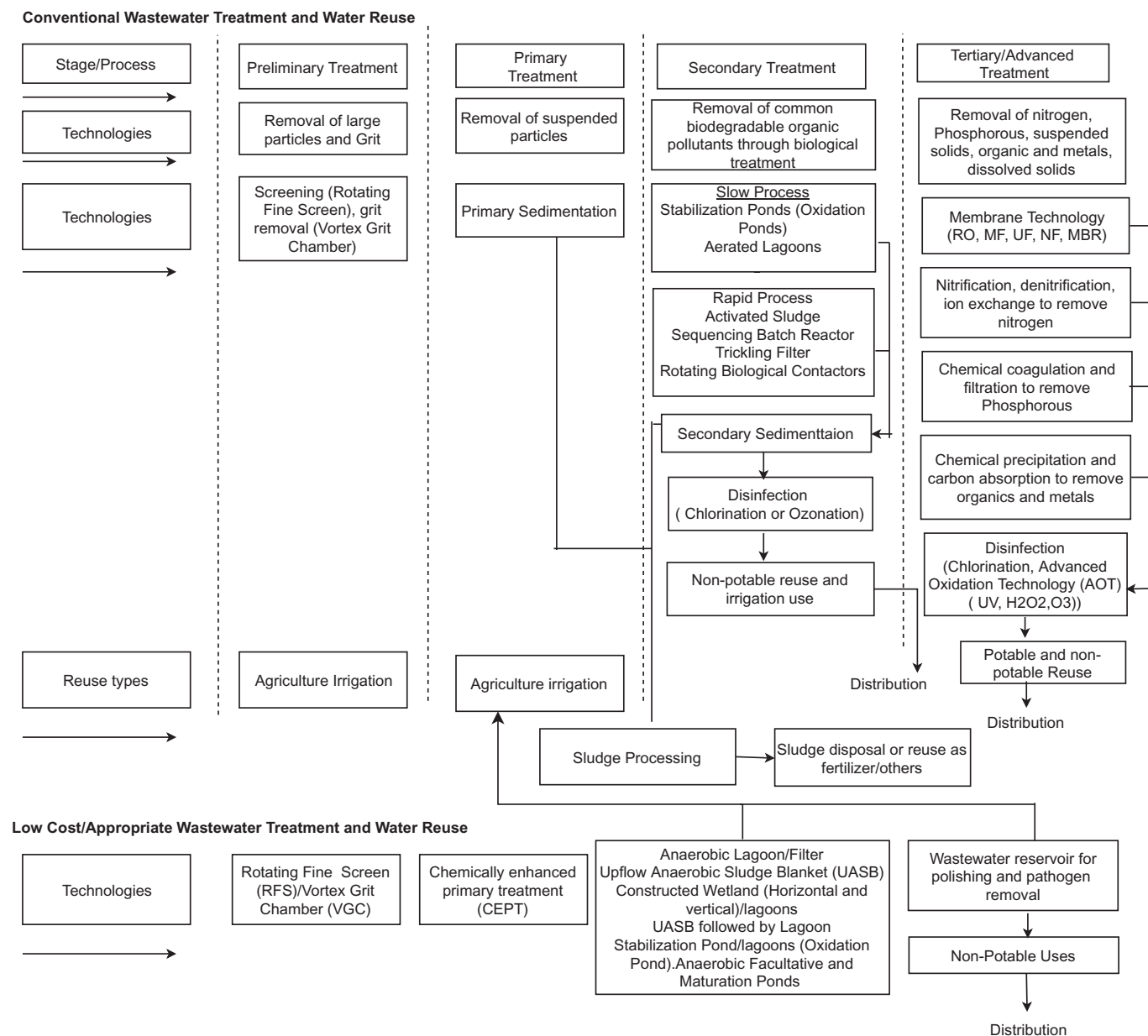


Fig. 6. Wastewater treatment and reuse (UNEP, 2005; Radcliffe, 2004; CSA, 2008; WHO, 1989; US EPA, 1992; Asano et al., 2007; CSBH, 1918).

energy intensity of various conventional wastewater technologies as studied is shown in Table 2 with references.

## 5.2. Conventional tertiary treatment (CTTT) and advanced water treatment (AWT) technologies and their energy intensities

Conventional Tertiary Treatment consists of filtration and disinfection and usually used by chlorine (Cooley and Wilkinson, 2012). AWT technology often is known as Membrane Technology and often follows a multiple barrier approaches of water treatment for removal of biological and chemical impurities using filtration, membrane separation, oxidation, adsorption, ultraviolet disinfection, and advanced oxidation. Among advanced treatment technologies, the use of MF, RO and UV disinfection is commonly practised worldwide (Verstraete and Vlaeminck, 2011; ASTE, 2012; Lafforgue and Lenouvel, 2015; Angelakis and Gikas, 2014; PUB, 2016). Purified water (Higher than drinking water quality is

now technically and economically feasible from centralised wastewater system using a multi-barrier approach followed by Advanced Water Treatment (AWT) technologies (Verstraete and Vlaeminck, 2011; ASTE, 2012; Angelakis and Gikas, 2014; Lafforgue and Lenouvel, 2015; PUB, 2016). AWT in centralised systems is used upstream of a Drinking Water Treatment Facility (DWTF) with or without a storage buffer (surface or groundwater) or downstream of a distribution system of a DWTF shown in Fig. 4 (WRRF, 2015). AWT usually involves high energy but can produce very high-quality water. Table 2 show specific energy intensity of AWT. Table 3 shows the energy intensity of Conventional Tertiary and AWT treatment trains available from the literature.

### 5.2.1. Reverse osmosis (RO)

Reverse Osmosis (RO) is the most frequently used technology for AWT (ASTE, 2012; Hummer and Eden, 2016; ISF, 2013). Treated water using RO complies with the microbiological standards for

**Table 1**

Specific Energy Intensity of conventional wastewater treatment technology or a combination of technologies.

Treatment Technology/combination of Technologies	Energy Intensity (kWh/kL)		References	Remarks
	Min	Max		
Conventional Activated Sludge (CAS)	0.1	1.9	*Stillwell et al. (2010), #Krzeminski et al. (2012)	*Small size plant (0–1 MGD) (26 plants average) 0.2 to 1.43 kWh/kL
Aerated Lagoon (AL)		1.93	Marcano (2012)	# 0.1 to 1.93 kWh/kL
Oxidation Ditch (OD)	0	1.82	Stillwell et al. (2010)	15 plants average
Biological Nutrient Removal (BNR)	0	0.42	Stillwell et al. (2010); Denn (2012)	19 plants average
Trickling Filter (TF)	0.18	0.48	Griffith (2003)	
Trickling Filter (TF) (Attached Growth)	0.13	0.17	Stillwell et al. (2010)	100-1 MGD plant size
TF and BNR	0.34	0.66	Stillwell et al. (2010)	5-1 MGD size plant
Sequential Bioreactor (SBR)	0	0.29	ERPI and WRF (2013)	
Waste Stabilization Pond (WSP)	0	1.2	Stillwell et al. (2010); EPRI and WRF 2013	5-1 MGD size plant
/Advanced Water Treatment (AWT) without Nitrification	0.31	0.69	Stillwell et al. (2010)	
Advanced Water Treatment (AWT) with Nitrification	0.32	0.78	Stillwell et al. (2010)	100-1 MGD plant size
Aeration with Nitrogen	0	0.29	Stillwell et al. (2010)	100-1 MGD plant size
OD and BNR	0.5	1	Stillwell et al. (2010)	5-1 MGD size plant
Advanced Textile/Packed bed filter		0.66	ASTE (2012)	100-1 MGD plant size
			Denn (2012)	

**Table 2**

Specific Energy Intensity of Advanced Water Treatment Technology or a combination of technologies or trains.

Technology/combination of Technologies	Energy Intensity (kWh/kL)		References	Remarks
	Min	Max		
MBR	4	12	Howell et al., 2004; Verrecht et al., 2010	First generation type Membrane (old type)
SMBR	0.2	4	Howell et al., 2004; Verrecht et al., 2010; Skouteris et al., 2014	Submerged Membrane Reactor (new type)
UV	0.02	0.8	*ASTE 2012; **Cooley and Wilkinson, 2012	0.5–0.8* and 0.02 to 0.04**
MF		0.12	ASTE (2012)	
Cl <sub>2</sub>		0.1	ASTE (2012)	
UF		0.18	ASTE (2012)	
BAC		0.2	ASTE (2012)	
NF		0.41	ASTE (2012)	
Ozone (O <sub>3</sub> )	0.032	0.2	##ASTE 2012; #Cooley and Wilkinson, 2012	#0.032 to 0.11, ## 0.2
RO	0.56	1.3	Scales et al., 2015, ASTE 2012	
Dual Membrane Filtration		0.4	Stillwell et al. (2010)	
Membrane Filtration		0.2	Stillwell et al. (2010)	
Filtration	0.02		ASTE (2012)	
Bio Phosphorous removal		0.57	ASTE (2012)	

drinking water (Levantesi et al., 2010). The energy intensity of RO technology to treat wastewater can be as high as 1.3 kWh/kL (Scales et al., 2015; ASTE, 2012; Griffiths, 2003). This value is much less than imported water from long distance source example for water supply in Southern California which has an energy intensity of 2.93 kWh/kL (CSA, 2008). In Orange County in California, Ground Water Replenishment System (GWRS) uses Conventional and AWT using RO, MF and UV with H<sub>2</sub>O<sub>2</sub> treatment. The energy requirement using these treatment trains is at least 50% lower than imported water from distant sources or other treatment options (1.68 kWh/kL<sup>11</sup>) (OCWD, 2018; Durham et al., 2001). The 'NEWater' technology in Singapore also treats secondary CAS effluent with MF/UF, RO, and UV for IPR and NPR since 2003 (PUB, 2011). Koksijde, Belgium, uses a tertiary treatment using UF and RO but also dune infiltration to enable sustainable groundwater management of the dune aquifer. For this, energy consumption over the period 2005–2009 was on average 0.15 kWh/kL for UF and 0.60 kWh/kL for RO (Van Houtte

and Verbaauwhede, 2008). Efforts are ongoing on how those technologies can produce high-quality water using less energy, for example, a conventional lime clarifier would produce a significant amount of sludge, which was very difficult to remove and plugs the RO membrane. Now current MF/RO produces virtually no sludge and requires less energy and chemicals. The Scottsdale Water Campus in Arizona treats wastewater using the first generation thin film RO membrane that removes dissolved materials in water at half of the operating pressure. The reduced pressure helps reduce energy consumption. The treated water is higher quality than drinking water standard but used to recharge groundwater instead for drinking (Van Leeuwen et al., 2010).

### 5.2.2. Membrane bioreactor (MBR)

Membrane Bioreactor (MBR) has emerged as a reliable treatment technology alternative to conventional treatment such as Activated Sludge (Metcalf and Eddy, 2007). The use of membrane technology is increasing in the water industry as a state of art technology for its robustness and capacity to produce high-quality water (Metcalf and Eddy, 2007; Judd, 2017) and other unique

<sup>11</sup> Calculated using energy intensity of water supply in Southern California (Navigant Consulting Inc. 2006).

**Table 3**  
Treatment Energy Intensity of Conventional Tertiary and Advanced Water Treatment trains to produce recycled water of various qualities (Potable and Non-Potable) used for different end uses.

Treatment Trains	Energy Intensity (kWh/kL)	References	End Uses
<b>Conventional Tertiary Treatment Trains</b>			
CBF-DM-Cl <sub>2</sub>	0.26	CSA 2008, Cooley and Wilkinson, 2012	Irrigation (Irr), Industrial use (Ind.)
FLOC-DFLT-UV/AOP	0.4	Cooley and Wilkinson, 2012, EPRI and WRF (2013)	Irrigation, Industrial use
CLAR-MFLT-Cl <sub>2</sub>	0.43	Cooley and Wilkinson, 2012, EPRI and WRF 2013	Irrigation, Industrial and commercial use (comm)
CBF-UV	0.45	CSA 2008, Cooley and Wilkinson, 2012	Irrigation, Industrial use (Ind)
RM-FLOCC-MFLT-UV	0.48	Cooley and Wilkinson, 2012, EPRI and WRF (2013)	Irrigation
<b>Advanced Water Treatment Trains</b>			
COAG-FLOC-CLR-UF-RO-UV/AOP	0.85	Cooley and Wilkinson, 2012, EPRI and WRF (2013)	Agriculture, industrial use
MF-RO-UV/AOP	0.97	Cooley and Wilkinson, 2012, EPRI and WRF (2013)	Groundwater recharge (GWR)
MF-RO-UV/AOP	1.03	Cooley and Wilkinson, 2012	Seawater intrusion barrier
<b>Advanced Water Treatment Trains</b>			
UF-RO-UV	1.07	Cooley and Wilkinson, 2012, EPRI and WRF (2013)	Industrial Use
MF-RO	1.23	Cooley and Wilkinson, 2012, EPRI and WRF (2013)	High-Quality Industrial Use
MF-RO	0.82	ASTE (2012)	Potable use
UF-RO	0.75	Van Houtte and Verbauwheide (2008)	Potable use
MF-RO	2.2	Cooley and Wilkinson, 2012, EPRI and WRF (2013)	High-quality/Potable water use
MF-RO-UV-H <sub>2</sub> O <sub>2</sub> -Cl <sub>2</sub>	0.93	Hall et al. (2009)	NPR-toilet flushing, gardening, watering lawn (*average of 8 plants).
Ozone-BAC-UF	0.58	Scales et al. (2015)	Potable water use
Ozone-BAC-MF	0.56	Scales et al. (2015)	Potable water use
MF-Ozone-BAC	0.15	Scales et al. (2015)	Potable water use

Where CBF-Coal bed Filtration, DM-Demineralisation, Floc-Flocculation, AOP-Advanced Oxidation Process, DFLT-Direct Filtration, MFLT-Membrane filtration, CLAR-Clarification, Cl<sub>2</sub>-Chlorination, MF-Media Filtration, Irrg-irrigation use, Ind-Industrial use, Comm-Commercial use, GWR-Groundwater Recharge.

advantages such as small spatial footprint and good disinfection capability (Abegglen, 2006; Metcalf and Eddy, 2007; Tadkaew et al., 2007; Skouteris et al., 2014). Earlier MBRs would be used for centralised/large scale applications but now it is being used for decentralised wastewater systems (Tadkaew et al., 2007). The short distances between wastewater generation and the recycled water facility make reuse of wastewater (permeate-final effluent of MBR plants) convenient in decentralised water recycling systems. Many developing countries such as China, Japan, India are also using this technology for the tertiary treatment of wastewater (Metcalf and Eddy, 2007; Judd, 2017; Kumar, 2013; Thippeswamy, 2018). Research carried out in Singapore by Public Utility Board (PUB) revealed that MBR is a robust and optimised technology, which can reduce energy more than other technologies and has exceptional ease of operation (PUB, 2011). Around 20 plants using MBR are ongoing in Singapore and China is also using this technology (PUB, 2011). MBR technology follows Activated Sludge Process (CAS), but sludge is separated by filtration instead by sedimentation (Abegglen, 2006). MBR has a wide range of energy intensity. The first generation aerobic MBR has specific energy intensity from 4 to 12 kWh/kL but the second generation MBR was known as Submerged MBR (SMBR) introduced in the market in 1989 overcome this high energy requirement. SMBR has specific energy intensity or demand 0.2–4 kWh/kL (Howell et al., 2004; Verrecht et al., 2010; Skouteris et al., 2014).

### 5.2.3. Submerged membrane bioreactor (SMBR)

In SMBR, air blowers are the most energy intensive component among other such as feed pump, suction pump when not gravity driven. The energy consumption by air blowers can vary from 50% to 100% (Ndinisa et al., 2006; Howell et al., 2004; Meng et al., 2008; Gander et al., 2000) of the total MBR energy. Verrecht et al. (2010)

did a model study on the evaluation of energy requirement for aeration of SMBR which shows the aeration energy can be optimised through operation of air blowers at lower fluxes and reduction in the membrane aeration (Verrecht et al., 2010). These findings also came from an evaluation of nine MBR plants mainly in the North America (California, Georgia, Florida, Ohio and Washington DC) (Pellegri and Kinnear, 2012) from primary data from energy companies. The energy intensity of 9 plants using this technology ranged from 1.4 to 4.23 kWh/kL operating between 4 and 20 MLD. The variables include the size of the plant, treatment processes before MBR and operation of the plants (Pellegri and Kinnear, 2012). However, most of these plants are using MBR to meet effluent water quality except a few which reuse the water for irrigation purposes (Pellegri and Kinnear, 2012). These MBR plants in the USA are used for secondary water treatment, but those require high capital and operating cost to maintain higher effluent water quality (US EPA, 2007). Though the energy intensity of this technology is higher than Activated Sludge Process (Zhang et al., 2003), it produces better quality which can be used for a wide range of non-potable purposes such as for toilet flushing and irrigation (Tadkaew et al., 2007). However, small-scale, decentralised water recycling systems using membrane bioreactors requires higher energy from 2 to 8 kWh/kL. Potable Water Reuse in centralised water recycling systems typically involves membrane technologies, which also consume high energy (Rygaard et al., 2011).

### 5.2.4. Biological Activated Carbon (BAC) filtration

Biological Activated Carbon (BAC) is considered as a good alternative to RO but involves less energy. A combination of ozone treatment and biologically active carbon filtration process can provide the same quality water to RO (Hummer and Eden, 2016).

### 5.2.5. Advanced Oxidation Technologies (AOT)

Use of AOT as part of recycled water treatment train has been proved as an efficient technology for AWT which reduces less energy. GWRS, as discussed earlier, uses AOT and UV, and the treated water is used for drinking. Here AOT uses less energy (0.23 kWh/kL) than other AOTs because of the generation of OH<sup>-</sup> radicals via the chemical reagents (Sharma et al., 2012). Sharma et al. (2012) applied this at Cap De Monte Decentralised Water recycling system to reduce the energy use. The same technology also has been used in Western Corridor Recycled water Plants in the SEQ region of Australia (Hall et al., 2009).

Cooley and Wilkinson (2012) report that conventional tertiary treatment has average energy intensity of 0.42 kWh/kL and Membrane treatment (AWT) has an average energy intensity of 1.1 kWh/kL.

Table 3 has been further explained and discussed in Section 8.2.

## 6. Energy intensity of centralised and decentralised water recycling systems

In this section, the four cases/situation as discussed in the Methodology have been used to review the energy intensity of various water recycling systems to understand how and where those four cases have been implemented around the world and what technologies used and the quality of water.

We found that only a few studies have been carried out in the last two decades to understand the energy intensity of water recycling systems for DPR, IPR, and NPR, (Burton et al., 1996; EPRI, 2002; Navigant Consulting Inc. 2006; Wilkinson, 2007; Kenway et al., 2008; CSA, 2008). Other studies mostly cover treatment technologies, regulatory requirements, product water quality, public acceptability, operation and management problems (CSA, 2008; Tchobanoglous et al., 2011; Grant et al., 2012; Lane et al., 2013; Angelakis and Gikas, 2014; Lafforgue and Lenouvel, 2015; Verstraete and Vlaeminck, 2011; Shehabi et al., 2012; PUB, 2011; Melbourne Water, 2017; US EPA, 2012; City of San Diego, 2015; Chong et al., 2012; Sharma et al., 2012; ISF, 2013; WRRF, 2012). Some life cycle studies focusing on wastewater treatment/water recycling systems have estimated the operational energy of water recycling systems (Foley et al., 2010; Lane et al., 2012; Lundin et al., 2000; Kavvada et al., 2016).

### 6.1. Centralised potable water reuse – ‘case 1’

#### 6.1.1. Centralised direct potable reuse (CDPR)

Direct Potable Reuse (DPR) (Fig. 4) is not very common globally due to related public acceptability issues (Rygaard et al., 2011; Waterteuse.org) even though Goreangab Water Reclamation Plant (GWRP) (21 MLD) in the city of Windhoek, Namibia is an excellent example of DPR and the longest running plant where recycling wastewater (mainly domestic wastewater), has been fed into the distribution system since the 1960s with no apparent adverse health impacts (Water Wheel, 2003; Grant et al., 2012; Agelakos and Gikas, 2014). This plant has been cited in many in their studies on recycled water reuse and it has attracted the world's attention. Lots of research is being done now to make DPR acceptable to the public as very high-quality drinking water is possible to produce with available technologies. Three DPR schemes have also been implemented in the USA – Big Spring (7 MLD), Wichita Falls (19 MLD) and Brownwood (5.7MLD) MLD), and further two in New Mexico (Cloudcroft (0.1 MLD)) and Beaufort West in South Africa (2 MLD) (Khan, 2013; ASTE, 2013).

However, studies have not been done to know the energy intensity of all these plants. The energy intensity of DPR at Goreangab Reclamation Plant was found 1.8 kWh/kL (Grant et al., 2012;

Lafforgue and Lenouvel, 2015; Lahnsteiner et al., 2018; Khan, 2013). Some studies mention that DPR could be a cost-effective option where the natural environmental buffer is not available, and/or the distance between treatment plants and agriculture land is long or requires dual pipes that are very expensive (Leverenz et al., 2011; Water in the West, 2013). Further, it can be cost effective and less energy intensive in areas where water is imported from long distant water sources such as in Southern California, or water is provided through desalination (CSA, 2008; Grant et al., 2012; Leverenz et al., 2011; Lahnsteiner et al., 2018). It has been estimated that potable reuse would consume 1–1.5 kWh/kL in Southern California compared with desalinated seawater, which requires 3.4–4.0 kWh/kL (CSA, 2008; Marsh, 2008; Grant et al., 2012).

#### 6.1.2. Centralised indirect potable reuse (CIPR)

A number of Indirect Potable Reuse (IPR) (defined in Fig. 4) plants have been installed especially in the USA, Singapore and Belgium (Grant et al., 2012). Their energy intensities from literature review have been discussed in Table 4. The World's most significant Ground Water Replenish System (GWRS) called Water Factory 21 at Fountain Valley of Orange County in California, has energy intensity from 0.65 to 1.22 kWh/kL (Grant et al., 2012; Verstraete and Vlaeminck, 2011; Navigant Consulting Inc. 2006). These values are less than long-distance water transfer<sup>12</sup> that requires 2.93 kWh/kL (Navigant Consulting Inc. 2006; Angelakis and Gikas, 2014). This plant treats about 97 GL per year (265 MLD) of domestic sewage using conventional (Primary and Secondary) and advanced treatments such as RO, MF and UV disinfection. The treated water recharges 20% of the extracted groundwater and prevents the intrusion of seawater. The water quality is higher than drinking water (Grant et al., 2012; Van Leeuwen et al., 2010; OCWD, 2018). It provides indirect potable water to about 0.85 million people in Northern and Central Orange County in (OCWD, 2018), making up 15% of the total water demand (Rygaard et al., 2011; Grant et al., 2012).

The first recycled water plant in the USA ‘Scottsdale Water Campus in Arizona’ treats 10 MGD (38 MLD) wastewater using advanced treatment. The treated water from this plant has a higher quality than that of drinking water standards, the water from this plant is used for irrigation of turf and golf courses. The plant complies with the 1980 Groundwater Management Act in Arizona (Van Leeuwen et al., 2010) which requires the use of natural or artificial recharge to replenish the volume of groundwater abstracted (Black and Veatch, 2002).

Singapore produces around 138 GL per year (378 MLD) of recycled water that meets 30% of Singapore's water requirement. Around 10 GL/year is used as indirect potable reuse through blending in a reservoir and subsequent drinking water treatment to provide 2.5% of the city's potable water requirement. The balance is used for non-potable purposes.

Two examples in Belgium demonstrate examples of IPR. In Koksijde, for the period 2005–2009, 40% of the secondary Conventional Activated Sludge (CAS) treated effluent provided 27% of drinking water demand. The remaining recycled water was used for non-potable applications including in-plant uses and dual pipe schemes for irrigation of crops, gardens, golf courses, and conservation areas (Grant et al., 2012). Similarly, in Wulpen, treated wastewater is used for groundwater recharge to supplement 70% of the groundwater withdrawal.

<sup>12</sup> Long distance water transfer here means bringing water from the hinterlands of a medium to large city.

**Table 4**

Energy Intensity of potable and non-potable water reuse with various scale or size of centralised water recycling systems.

Size (MLD)	Energy Intensity (Potable Water Quality) kWh/kL	Energy Intensity (Non-Potable Water Quality) kWh/kL
<5	2–0.75	2–0.48
5–75	0.9–0.4	0.75–0.3
75–200	0.8–0.2	0.55–0.25
>200	<0.8	<0.55

### 6.2. Centralised Non-Potable water reuse (CNPR) – ‘case 2’

Use of secondary or tertiary treated wastewater for agricultural irrigation (including peri-urban agriculture) (Fig. 3) has been practised over 5000 years (Agelakos and Gikas, 2014). For example, in Israel, 73% of its municipal sewage is treated and reused for agriculture (Agelakos and Gikas, 2014).

Currently, recycled water is commonly used for non-potable water reuses. Such uses of NPR from the centralised system (Fig. 3) requires dual pipe systems that involves a large amount of energy for pumping the water to the end users (Navigant Consulting Inc. 2006; Water in the West, 2013; ISF, 2013b). Pumping energy intensity of recycled water schemes for irrigation in the South-East Queensland (Australia) varies between 0.19 and 0.44 kWh/kL (Hall et al., 2009). Singapore used most of its recycled water (high quality) as discussed earlier for NPR, mainly for industrial purposes and meet 32% water demand. It accounts for 9% of municipal water supply (Grant et al., 2012).

The energy intensity of NPR of these plants and others have been discussed in Table 4.

### 6.3. Decentralised direct potable reuse (DDPR) – ‘case 3’

Even though very high-quality water is used for non-potable purposes at Rose Hill and Darling Harbour (Table A.4 in Appendix A), there is no example of potable water reuse in decentralised water recycling systems. Bangalore also produces potable drinking water quality recycled water at Cubbon Park but it is used for non-potable purposes such as horticulture, flushing toilets, washing cars, watering lawn and gardening (Kumar, V.C, 2013 and Thippeswamy, 2018).

### 6.4. Decentralised Non-Potable Reuse (DNPR) – ‘case 4’

Decentralised water recycling systems as discussed earlier in Section 3.2 though have several advantages over centralised systems. (Sharma et al., 2012; ISF, 2013; Kavvada et al., 2016). The use of decentralised wastewater/recycling systems is increasing because of their multiple advantages such as protection of water bodies, ease of operation, onsite use of recycled water, avoidance of delayed implementation of centralised infrastructure. Further, a wide range and case-specific technologies can be used, and use of onsite use of recycled water help reduce pumping energy (Seigrist et al., 2013; Denn, 2012; Masood et al., 2009). However, a very limited number of studies have assessed the energy intensity of decentralised systems as shown in Table A.4 in Appendix A. The energy intensity of decentralised systems have higher energy intensity (Sharma et al., 2012; ISF, 2013; Kavvada et al., 2016) ranging from 1.7 to 10.53 kWh/kL (Table A.4 in Appendix A).

Japan has implemented over 2500 decentralised water and wastewater systems. The treated water from these plants is used by the residents (Yamagata et al., 2003). The Metropolitan Government Facilities in Tokyo used this recycled water for toilet flushing,

gardening and other purposes such as cooling purpose (Gikas and Tchobanoglous, 2008; Bernal and Restrepo, 2012). Bangalore (India) has installed over 2000 decentralised wastewater treatment systems at individual/residential complexes under the ‘Zero Liquid Discharge’ programme. However, only 200 of these plants are reportedly functioning because of high operational and maintenance cost (Kuttuva et al., 2016). The treated water from these plants is used for toilet flushing and urban irrigation.

In the USA market, decentralised wastewater treatment plants alone represent 30% of new construction, and they serve more than 60 million people in the USA (roughly one-quarter of the population of the country). A well-cited example is the Solaire residential complex in New York (Bernal and Restrepo, 2012). Though the USA has been using decentralised systems for over a century, the systems are still not well understood compared to centralised wastewater systems with regard to their design, operation, and maintenance (Water Online, 2014).

Recently, larger decentralised water recycling systems (distributed systems) have been promoted (in between large centralised and lot/stand-alone systems). The largest such plant is the Tillman wastewater treatment plant in Los Angeles which has a capacity of 320 MLD (Bernal and Restrepo, 2012). The Los Angeles County Sanitation District has seven satellite wastewater treatment plants that are used to reuse wastewater. In Australia for example, such schemes include Distributed Water recycling system (6 MLD) at Rosehill and the sewer Mining system at Darling Harbour, both in Sydney (Mitchell, 2004; ISF, 2013).

Energy Intensity of 37 water recycling systems as implemented around the world using centralised and decentralised systems have been shown in Figure-7, the details (technologies and specific purposes) of which have been discussed in Table A.3 and Table A.4 in Appendix A. This has been further explained in the discussion Section 8.1.

## 7. Variation of energy intensity with scale/size of a water recycling systems

With an extensive review, only limited data were found to understand how energy intensity varies with the size of a plant for a particular treatment technology. To understand the variation of energy intensity with the size of a plant, we need available energy intensity data with the same technology and treatment train. EPRI (2002), EPRI and WRF (2013) and ASTE (2012) have done some extensive studies on centralised water recycling systems how energy intensity varies with the size of a plant (interpolated data surveyed from a good number of plants in the USA). Some other data were found from studies done by Cooley and Wilkinson (2012), Eaton (2013) and Scales et al. (2015). Those have been tabulated in Table A.5 in Appendix A. Some energy intensity data of recycled water plants using the same treatment train and RO technology was found from SEQ region but their individual capacity could not be found in the literature (Hall et al., 2009).

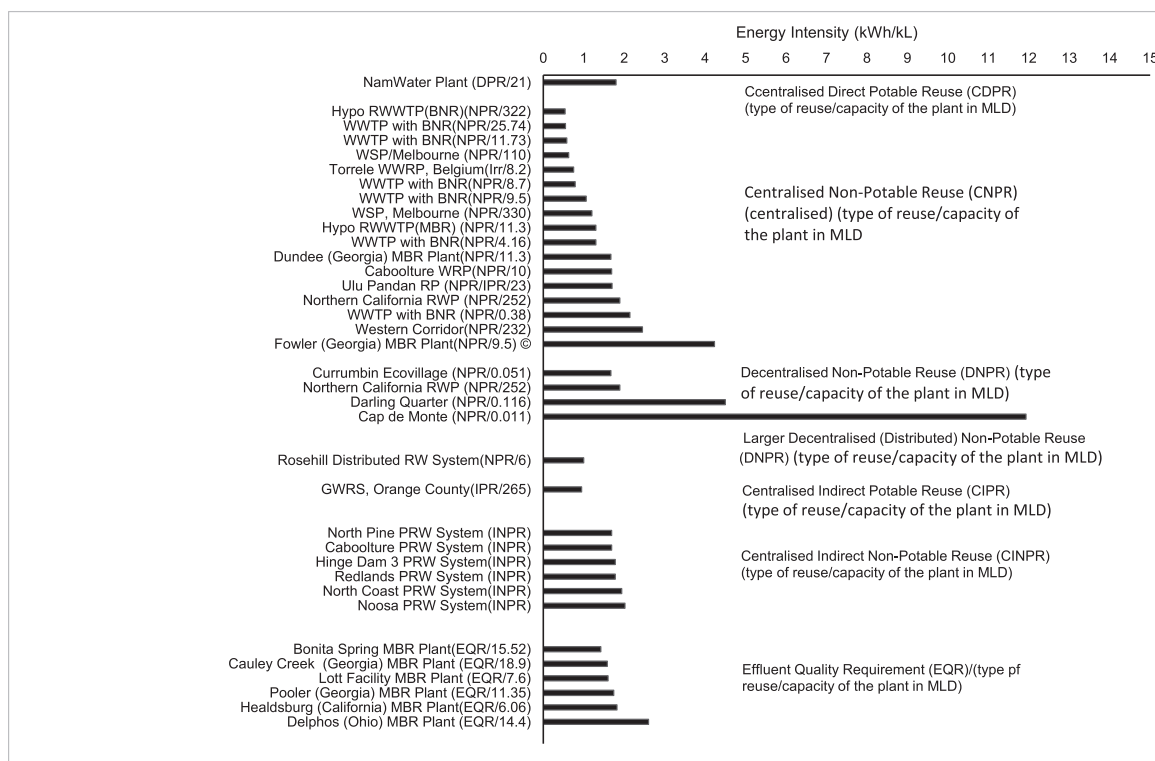


Fig. 7. Energy Intensity of centralised and decentralised recycled water plants around the world available from literature (drawn from data in Table A.3 and Table A.4 in Appendix A).

Only a few studies have assessed energy intensity of small-scale water systems, and mainly those have been conducted in Australia and USA (Sharma et al., 2012; Stokes and Horvath, 2010; Kavvada et al., 2016). They found that small-scale, decentralised systems have the high-energy intensity and GHG emissions are also high (Sharma et al., 2012; Kavvada et al., 2016). He compared one centralised and the other decentralised wastewater system in California and showed that the large scale of economies of a centralised plant can have the environmental impacts less than a fifth of that of a decentralised system for the same volume of wastewater treated. This is because as the centralised water recycling systems reduce greenhouse gases by flaring methane gas produced from treatment processes while in decentralising water recycling systems methane is directly released into the air. However, the study also states that the energy and GHG emissions in decentralised wastewater/water recycling systems can be low if a significant amount of wastewater is recycling (Shehabi et al., 2012). This illustrates that distributed water recycling systems might have less energy and GHG emissions.

## 8. Discussion

Our objective was a broader literature and data review on the energy intensity of water recycling systems, with attention to the effect of scale and technology.

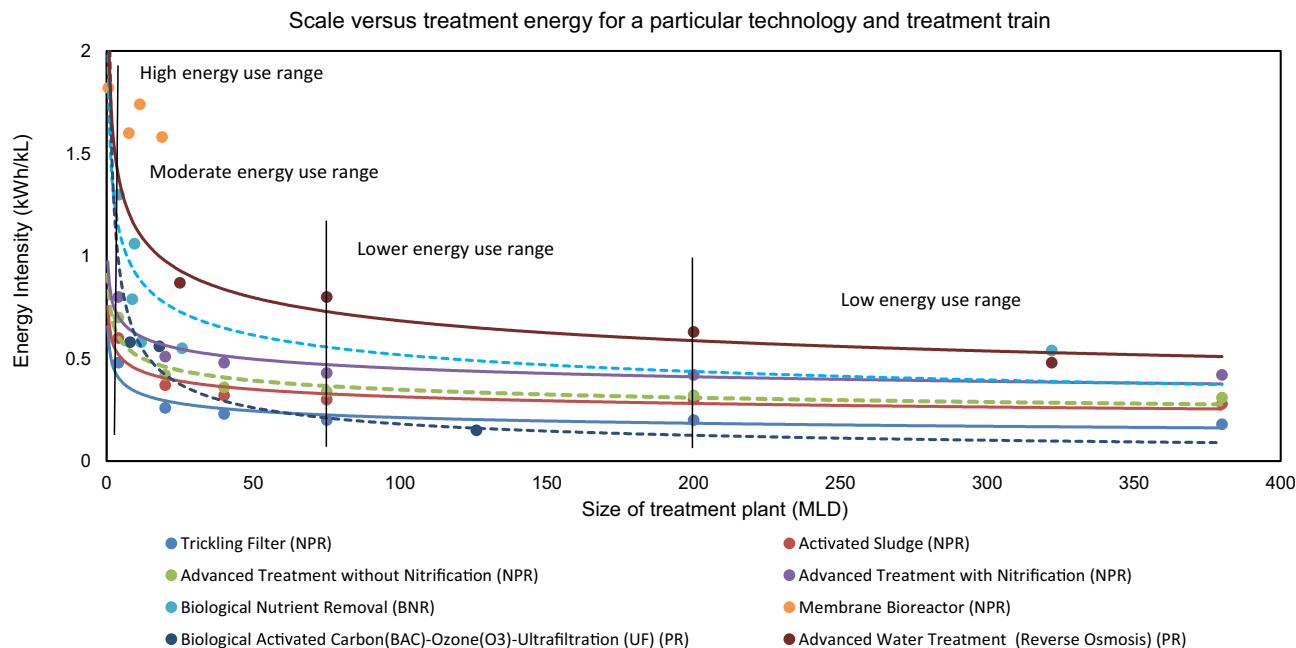
### 8.1. Scale impact on energy intensity

How energy intensity of a water recycling system varies with a particular technology given the same treatment train, has been shown in Fig. 8 derived from data mentioned in Table A.5 in Appendix A from the literature review. These data are based on

centralised water recycling systems and treatment energy intensity only.

From Fig. 8, it is clear that the energy intensity of a centralised water recycling system decreases with increasing size because of the scale of economies for a particular technology given the same treatment train. Further, it can be observed that for all treatment technologies shown in Fig. 8, the systems having a capacity less than 5 MLD have higher energy intensity. The energy intensity decreases moderately between 5 and 75 MLD. After 75 MLD up to 200 MLD, the energy intensity further reduces at a slow rate. For all systems greater than 200 MLD capacity, the energy intensity decreases at a very slow rate. Kavvada et al. (2016) reviewed literature for small-scale MBRs (0.02–2 MLD). They also found a trend of decreasing energy intensity with increasing size of a plant. Further, Hall et al. (2009) tried to understand how energy intensity varies with an average dry water flow of a particular STP in South East Queensland (SEQ). Our review and data analysis also shows the decreasing trend of energy intensity with increasing size of a plant given the same treatment train but for a wide range of scales (small, medium and large) and technologies of water recycling systems. The energy intensity to produce various water quality under a various range of scales of centralised water recycling systems from Fig. 8 are tabulated in Table 4.

For existing or implemented centralised potable water recycling systems as described in Table A.3 in Appendix A, we found that energy intensity for Direct Potable Reuse (DPR) ranges from 1.7 to 2.22 kWh/kL. DPR can be less energy intensive than systems that are dependent on the long transfer of water (Navigant Consulting Inc. 2006) (2.93 kWh/kL) or desalination (2.2–5.8 kWh/kL) (Navigant Consulting Inc. 2006; Navigant Consulting Inc. 2010; Cooley and Wilkinson, 2012; Hammer and Eden, 2016; Lahnsteiner et al., 2018) or IPR where the engineering buffer is



**Fig. 8.** Variation of Energy Intensity with size of recycled water plant with particular technology using data of centralised systems (EPRI, 2002; EPRI and WRF, 2013) (data converted from kWh/MGD to kWh/MLD) (projected data from surveyed plants); Cooley and Wilkinson (2012); Eaton (2013); Scales et al. (2015) and Kavvada et al. (2016) (existing plants). All data represent treatment and in-plant pumping energy only.

expensive (Lahnsteiner et al., 2018). Pumping back the recycled water to end users can be very energy intensive for non-potable water reuse using dual pipe system separate from existing potable pipe system as centralised wastewater treatment plants are usually situated downgradient from most cities.

Current decentralised or small systems have a higher range of energy intensity of 0.4–2 kWh/kL (using centralised data). Current implemented decentralised water recycling systems (Table A.4 in Appendix A) shows that much smaller decentralised systems between 11 kLD to 55 kLD have a quite high range of energy intensity from 1.3 to 10.5 kWh/kL (excluding pumping).

Larger decentralised water recycling systems (distributed systems) are very few and have been pioneered by Australia. But sufficient data are not available on the energy intensity of such larger decentralised systems. We found that distributed water recycling system at Rose Hill in Sydney has lower energy intensity of 1 kWh/kL, the capacity of which is 6 MLD. The size is out of the range of small centralised systems (0–5 MLD) having high energy intensity. This can be illustrated that higher capacity decentralised systems greater than 5 MLD has lower energy intensity.

Centralised large systems though have lower energy intensity but conveying recycled water back to the users involves a good amount of energy 0.34 kWh/kL on average (Hall et al., 2009). Cooley and Wilkinson (2012) show the average is 0.37 a slightly higher and can vary from 0.26 to 0.79 kWh/kL. On the other hand, small decentralised recycled water systems have higher energy intensity than large centralised systems. But larger decentralised systems (known as distributed systems) have lower energy intensity than small decentralised water recycling systems.

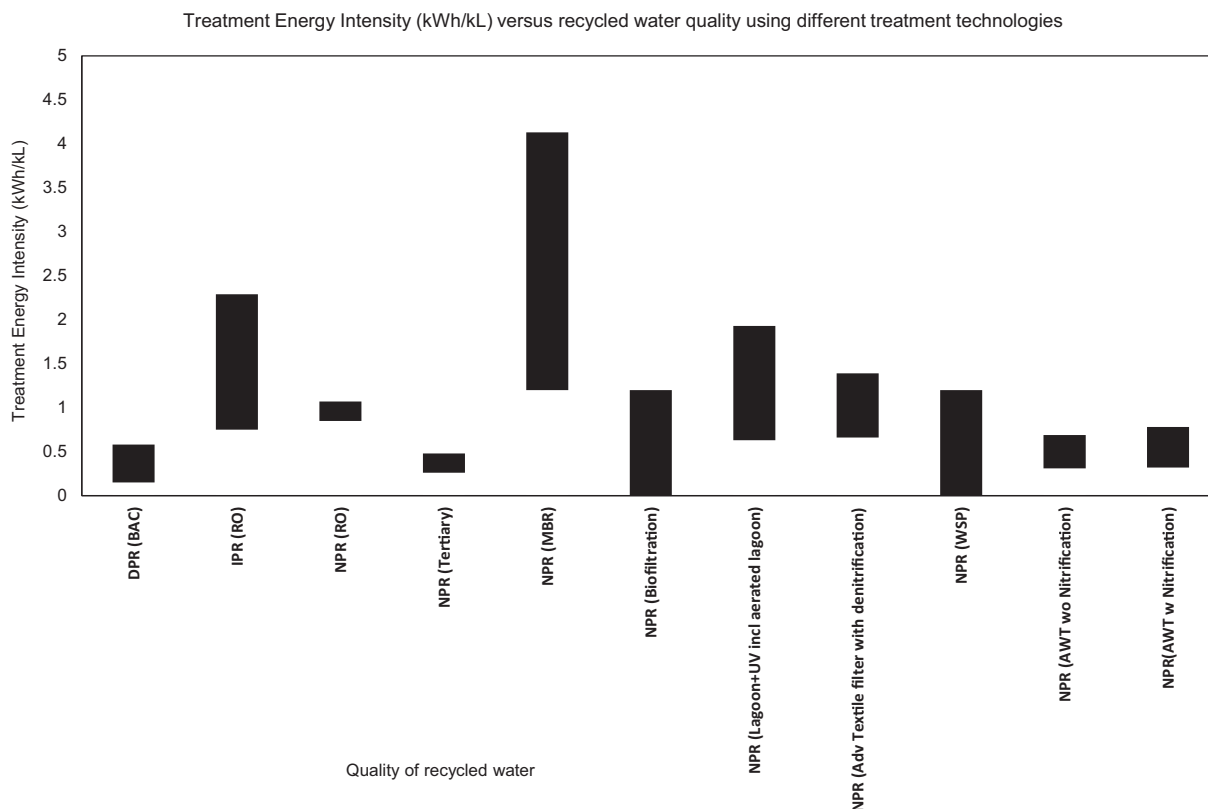
Past studies show that life cycle energy and GHG emissions in decentralised wastewater/water recycling systems can be lowered if a significant amount of wastewater is recycled (Shehabi et al., 2012; Stokes and Horvath, 2010). This further strengthens the view that larger decentralised water recycling systems (distributed

water recycling systems or mid-scale systems) have less energy intensity. From our study, the range of scale between 5 and 200 MLD can be considered as larger decentralised systems (distributed systems) through which a larger volume of recycled water can be produced and reused. Thus these systems have potential to reduce energy intensity, especially where water is supplied from long distant sources in centralised systems and further these can reduce conveyance or pumping energy significantly as recycled water can be reused at the point of generation. In these systems, the residuals (effluent) from plants can be discharged into the existing sewerage network and conveyed to centralised treatment plants. Such systems, therefore, follow basin approach of water management than stand-alone smaller decentralised systems (where no back up of centralised water) and thus those are sustainable, robust and resilient systems.

## 8.2. Technology implications for energy intensity

From specific energy intensity of various conventional and advanced treatment technologies tabulated in Tables 1 and 2 respectively, it is very apparent that the selection of an appropriate technology has significance in reducing the energy intensity of a wastewater treatment/water recycling system.

Table 1 explains that the energy intensity of conventional wastewater treatment technologies can vary from 0.1 to 1.9 kWh/kL across different technologies. Tricking Filter with attached growth has much lower energy intensity from 0.13 to 0.17 kWh/kL. Tricking Filter if used in combination with BNR has energy intensity 0.34 to 0.66 kWh/kL and can remove nutrients and such water can be used for some non-potable uses (Table A.1 in Appendix A). On the other hand, Oxidation Ditch (OD) and Aerated Lagoon (AL) have higher energy intensity above 1.5 kWh/kL. Advanced Textile/Packed bed filter also has a lower energy intensity. All these technologies are used in centralised systems to produce secondary/tertiary



**Fig. 9.** Energy Intensity to produce various 'fit for purpose' water using centralised systems but for decentralised systems it needs to add energy intensity for secondary treatment based on technology choices based on Table 3.

treated water but Activated Sludge and Advanced Textile/Packed bed filter are used now in decentralised water recycling systems (Sharma et al., 2012). Activated Sludge usually has higher energy intensity than Trickling Filter. If we look at Fig. 6 and Table 1, secondary treated water from centralised wastewater treatment systems can be used for many some non-potable purposes such as for irrigation of parks, playgrounds, non-food crops, building construction, industrial cooling and environmental reuse.

The energy intensity of advanced water treatment technologies can vary from 0.02 to 4 kWh/kL (Table 2). RO for advanced water treatment has lower specific energy intensity ranging from 0.56 to 1.3 kWh/kL and a commonly used technology. MBR has still higher energy intensity. Old type MBR has energy intensity from 4 to 12 kWh/kL but again submerged MBR has lower energy from 2 to 4 kWh/kL. Use of MBR is increasing both in centralised and decentralised water recycling systems due to its several advantages as discussed in Section 5.2. MBR can be used in place of conventional activated sludge and a robust technology. MBR if used in small-scale decentralised systems can consume 2–8 kWh/kL (Rygaard et al., 2011). MBR, SBR, MBBR, and RO though have higher energy intensity, those can produce high-quality water even than the drinking water standards. However, the same quality water can be produced using low energy technologies and follow multiple barriers, as followed in Windhoek in Namibia and Caboolture that use activated carbon followed by other treatments. The recycled water for non-potable uses can be produced using less energy than 0.5 kWh/kL. However, some industrial and other uses that need nutrient removals require higher treatment and thus higher energy.

The treatment energy intensity of various conventional tertiary

treatment and advanced water treatment trains to various quality of recycled water has been drawn in Fig. 9 using data in Tables 4 and 2. From Fig. 9, it can be observed that non-potable water can be produced using centralised systems with even less energy from 0.26 to 0.48 kWh/kL (in centralised system energy intensity up to secondary treatment is sunk<sup>13</sup> energy) but it can be as high as 4 kWh/kL if MBR is used. The potable water can be produced with less energy from 0.15 to 0.58 even using AWT such as BAC followed in GWRP. The Energy Intensity of Advanced Water Treatment trains for higher quality water can vary from 0.15 to 2.2 kWh/kL (Table 3). BAC has much less energy intensity from 0.15 to 0.58 kWh/kL to produce potable drinking water. For decentralised systems, energy intensity for secondary treatment should be added to these values to get the total energy intensity. The energy intensity of conventional secondary wastewater treatment which depends on the size of a plant and treatment technology can be found from Table 1 and selected. Cooley and Wilkinson (2012) reports that energy intensity of secondary wastewater treatment can range average from 0.36 to 0.6 kWh/kL for 5 to 200 MLD and the highest can be from 0.55 to 0.82 kWh/kL but still can vary for various other factors.

From Table A.3 and Table A.4 in Appendix A, it is observed that current trend is to produce high-quality recycled water better than drinking quality for all non-potable purposes (just like use of single high quality for all purposes by centralised water supply system) example for Caboolture in Australia (the same treatment train is used in Goreangab Water Reclamation Plant (GWRP) in Namibia for

<sup>13</sup> Here, 'sunk energy', we meant the constant or mandatory energy in centralised wastewater systems required for wastewater treatment for its safe disposal (effluent).

<sup>14</sup> There is no evidence of Decentralise Potable Reuse.

DPR), Singapore, SEQ region using AWT technologies such as MBR and RO. Stringent water quality standards and risk concerns drive the additional use of energy to produce the high-quality recycled water (Mukheibir and Mitchell, 2018) which level of quality is not necessarily required. To overcome this, regulators and policy-makers should understand the necessity to formulate appropriate regulations/standards for various end uses, rather than using uniform standards for all end uses of recycled water. Using 'Fit for Purpose' water together with the selection of appropriate technologies for the associated water quality, the energy intensity of a water recycling system can potentially be reduced. A mixed quality recycled water (tailored water) is possible to produce in the same treatment plant and then distribute to the end users (both in centralised and decentralised and distributed water recycling systems) (Prieto et al., 2013). However, little attention has been given to introducing desired quality or 'fit for purpose' water use and thereby the use of appropriate technologies to reduce energy use for urban water services.

Selection of treatment train is also very important to reduce the energy intensity of a recycled water system. For example, many developed countries use ozone that requires 40 times more energy than chlorine which can also kill all pathogens. In addition, advanced technology MF can kill pathogens, and has lower energy intensity than Ozone as mentioned in Table 2.

Further, the level of treatment also depends on wastewater influent characteristics/secondary water characteristics. Quantification or knowing the wastewater characteristics (Table A.2 in Appendix A) can improve the selection of appropriate technologies to produce the desired water quality, and thereby reduce energy consumption in many cases. By segregating industrial wastewater from municipal wastewater, energy consumption can be reduced for municipal water reuse and this is possible if distributed water recycling systems are followed.

The regulators and policymakers also need to discourage the installation of small decentralised water recycling systems and rather select larger decentralised (distributed systems) to reduce overall energy use for urban water services and GHG emissions. Producing recycled water from centralised systems require less energy as the energy requirement up to secondary treatment is a sunk energy but conveying the recycled water back to the distant end users involves a good amount of energy. It can still be less energy intensive than long distant water transfer or desalination.

Finally, there is large scope for reduction of energy intensity of a water recycling system which requires careful planning and design such as selection of the size or scale of a system, efficient pump size, proper location of the plant that can reduce pumping, selection of an appropriate technology and treatment train and nonetheless the efficient operation and maintenance of the system.

## 9. Conclusion

Consideration of energy use to produce recycled water and its reuse is very important, as recycled water use is increasing. We used four cases a) Centralised Potable Reuse b) Centralised Non-Potable Reuse c) Decentralised Potable Reuse and d) Decentralised Non-Potable Reuse to guide a comprehensive literature and data review. Our aim was to understand how the energy intensity of a water recycling system varies with different scales and technologies.

We found that the energy intensity of a centralised water recycling system decreases with its increasing scale or size both for

Potable and Non-Potable Reuse. The treatment energy intensity for centralised systems having a capacity less than 5 MLD varies from 0.48 to 2.0 kWh/kL for non-potable reuse and 0.75 to 2.0 kWh/k for potable reuse. The energy intensity for sizes between 5 and 200 MLD varies from 0.2 to 0.9 kWh/kL for potable reuse and from 0.25 to 0.75 kWh/kL for non-potable reuse. For systems greater than 200 MLD, the energy intensity is less than 0.8 kWh/kL for potable reuse and 0.55 kWh/kL for non-potable reuse. But the current centralised water recycling systems have energy intensity from 0.65 to 1.4 kWh/kL (excluding pumping or for distribution energy) for Potable Water Reuse and from 0.6 to 1 kWh/kL for non-potable reuse. Due to unavailability of segregated, consistent and necessary data, scale versus energy intensity could not be derived from practised water recycling systems. However, it was found that pumping energy is significant for centralised reuse. Pumping energy for raw sewage collection can vary from 0.47 to 1.06 kWh/kL and for that for distribution of recycled water can vary from 0.19 to 1.43 kWh/kL.

The data available on the energy intensity of decentralised water recycling systems show that smaller systems (in kilolitre scale) can have high energy intensity from 1.11 to 10.5 kWh/kL (only treatment and in-plant pumping) for non-potable water reuse. Using decentralised recycled water system, potable water can be generated at an energy intensity of 2.2 kWh/kL but not in practice (Hall et al., 2009).

Larger decentralised water recycling systems (known as distributed systems) ranging from 5 to 200 MLD have lower energy intensity than small decentralised systems.

'Fit for purpose' water in distributed water recycling systems could have the potential to reduce the energy intensity of a water recycling system particularly if it helps avoid pumping of water and wastewater. Current water recycling systems tend to be designed to produce high-quality water even better than drinking quality using advanced water treatment but such high-quality water is usually not necessarily required for all non-potable uses.

More systematic data focusing on the whole water use cycle are required to undertake further analysis and thereby provide planners with rigorously assessed alternatives. In particular, it is necessary to improve the separation of data for treatment and transmission (ie pumping for distribution and sewage collection). Future research is required to understand how energy intensity of water recycling systems changes particularly with various technologies.

## Acknowledgment

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## Appendix A

**Table- A.1**

Recycled water Standards for various types and specific uses (US EPA, 2004; NRMCC, 2006; NHMRC and NRMCC, 2011; DOE, 2013; Crook et al., 2005)

Type of Use	Specific Use	Australian Guidelines on Water Reuse	US EPA Guidelines for Water Reuse	Japan	Treatment
Non-Potable Water Reuse	Toilet and Urinal Flushing (residential)/car washing, washing lawn, wall, path or streets	pH 6.5–8.5 NTU ≤2 NTU Cl <sub>2</sub> residual ≥1 mg/L after 30 min	pH = 6–9 ≤ 10 mg/L BOD ≤2 NTU No detectable fecal coli/100 mL ≥1 mg/L Cl <sub>2</sub> residual	Total Coli/100 mL ≤ 10 Chlorine residual, mg/L-trace pH-5.8-8.6 Appearance-not unpleasant Odour- not unpleasant	Secondary Filtration Disinfection (Tertiary and pathogen reduction) Secondary and pathogen reduction
	Toilet Flushing (office and factory-closed system)/industry washdown water	TC < 10 cfu/100 mL Cl <sub>2</sub> residual ≥1 mg/L after 30 min TC < 10 cfu/100 mL			
	Landscape Irrigation (uncontrolled public access) such as open space, parks, playgrounds, dust suppression, construction work)	pH 6.5–8.5 NTU ≤2 NTU Cl <sub>2</sub> residual ≥1 mg/L after 30 min TC < 10 cfu/100 mL		Not detected pH-5.8-8.6 Chlorine residual, mg/L ≥ 0.4 mg/L Appearance-not unpleasant Odour- not unpleasant	Secondary and pathogen reduction including helminth reduction for cattle grazing
	Landscape Irrigation (controlled public access) such as open space, parks, playgrounds, process food crops, non-food crops, aesthetic impoundments, dust suppression, construction work, industrial cooling, environmental reuse	TC < 10 cfu/100 mL	pH = 6–9 ≤30 mg/L BOD ≤30 mg/L TSS ≤200 fecal coli/100 mL ≥1 mg/L Cl <sub>2</sub> residual	Not detected pH-5.8-8.6 Appearance-not unpleasant Turbidity, NTU≤10 BOD, mg/l ≤ 10 Appearance-not unpleasant Odour- not unpleasant	Secondary
Indirect Potable Water Reuse	Groundwater Recharge of non-potable aquifers by spreading		Site-specific and use-dependent		Site-specific and use-dependent Primary (minimum)
	Groundwater Recharge of non-potable aquifers by injection		Site-specific and use-dependent		Site-specific and use-dependent Secondary (minimum)
	Groundwater Recharge of potable aquifers by spreading		Site-specific Meet drinking water standards after percolation through the vadose zone		Secondary Disinfection May also need filtration & advanced wastewater treatment Groundwater
	Groundwater Recharge of potable aquifers by injection		Includes the following: pH = 6.5–8.5 ≤2 NTU No detectable faecal coli/100 mL ≥1 mg/L Cl <sub>2</sub> residual ≤3 mg/L TOC ≤0.2 mg/L TOX Meet drinking water standards		Secondary Filtration Disinfection Advanced wastewater treatment
	Surface water as a buffer		Includes the following: pH = 6.5–8.5 ≤2 NTU No detectable faecal coli/100 mL ≥1 mg/L Cl <sub>2</sub> residual ≤3 mg/L TOC ≤0.2 mg/L TOX Meet drinking water standards		Secondary Filtration Disinfection Advanced wastewater treatment
Direct Potable Reuse	For drinking	Physical constituents: Turbidity-52.96 NTU, Alkalinity-217.7 mg/L, Colour-71.88 mg/L Pt, COD-43.32 mg/L, DOC-15.1 mg/L, Total trihalomethanes-168.75 µg/L			

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**Table- A.1** (continued)

Type of Use	Specific Use	Australian Guidelines on Water Reuse	US EPA Guidelines for Water Reuse	Japan	Treatment
		UV254–0.36 ab s/cm Macro Elements: Aluminium-Al 0.15 mg/L, Ammonia-0.1 N mg/L, Iron- Fe 0.1 mg/L, Manganese-Mn 0.025 mg/L Microbiological Indicators: Heterotrophic Plate Counts-100/1 mL, Total Coliforms-0/100 ml, Faecal Coliform-0/100 ml, Enteric Viuses-0, Escherichia Coli-0 Faecal Streptococci-0/100 ml, Clostridium spores-0/100 ml, Clostridium viable cells 0/100 ml Biological Indicators: Chlorophyll-1µg/, Giardia - Greater of 1/100 L or a 6 log removal, Cryptosporidium - Greater of 1/100 L or a 6 log removal, Disinfection by-products-Total Trihalomethanes- 20 1µg/L			Primary Secondary Advanced water Treatment

**Table A.2**

Typical characteristics of domestic wastewater in decentralised systems commonly used for decentralised and distributed water recycling system design (Seigrist et al., 2013)

References		Lowe et al., 2009		US EPA	Crites and Tchobanoglous (1998)
Parameter	Unit	Median	Range	Range	Range
TSS	mg/l	232	22–1690	155–330	100–350
Oil and grease	mg/l	50	10–109	n/a	50–150
BOD5	mg/l	420	112–1101	155–286	110–400
COD	mg/l	849	129–4585	300–660	250–1000
TOC	mg/l	184	35–738	n/a	80–290
Total Nitrogen	mg-N/l	60	9–240	26–75	20–85
Total Phosphorous	mg-P/l	104	0.2–32	6–12	4–15

**Table A.3**

Energy Intensity of Centralised Potable and Non-Potable Reuse (Case 1 and Case 2 of Fig. 1 in the Main Text)

Type of use	Name of Recycled water Plant/ Location	Capacity (MLD)	Purpose of Use and Source of water	Treatment Technologies and water quality	Energy Intensity (kWh/kL)	References	Remarks
Direct Potable Reuse (DPR)	Goreangab Reclamation Plant (NamWater Plant) in Windhoek, Namibia	21	Meets water demand of 35% of the city population (250,000) moreover, 50% in a severe drought since 1968 Secondary treated water using CAS	PAC-PO-COAG-DAF-RSF-MO-BAC-GAC-UF-Cl <sub>2</sub>	1.80 kWh/kL* (Treatment 1.4** kWh/kL and Distribution-0.46 kWh/kL#)	Grant et al., 2012 * Lafforgue and Lenouvel (2015) ** Lahnsteiner et al., 2018 reports that it is 0.88 kWh/kL #Khan, 2013 Khan (2013), ASTE 2013; Tchobanoglous (2013)	includes pumping
	Cloudcroft New Mexico, USA	0.1	Started in 2011. Contributes to 15% of blended raw water in the pipeline.	MBR-CL-RO-UV + H <sub>2</sub> O <sub>2</sub> –blending-UF-UV-GAC-Cl <sub>2</sub> -Distribution	n/a	Khan (2013), ASTE 2013; Tchobanoglous (2013)	
	Big Spring, West Texas, USA	10	Started in 2013. Contributes to 15% of blended raw water in the pipeline. (30, 0000 Pop <sup>n</sup> ).	MF-RO-UV + H <sub>2</sub> O <sub>2</sub> Raw water: Filtered Secondary effluent	n/a	Khan (2013), ASTE 2013 Tchobanoglous (2013)	
	Beaufort West Municipality, South Africa	2	Started in 2011. Contributes to 15% of blended raw water in the pipeline.	MF-RO-UV + H <sub>2</sub> O <sub>2</sub> – Cl <sub>2</sub> Raw water: Conventional Tertiary Treated effluent	n/a	Khan (2013): ASTE 2013;	
	Wichita Falls, Texas, USA	19	Started in 2014–2015 (50% blended with untreated lake water in a splitter box).	Cl <sub>2</sub> , NH <sub>3</sub> , Coagulation, sedimentation, MF, RO, UV, Lagoon	n/a	Lahnsteiner et al. (2018)	
	Brownwood, Texas, USA	5.7	Blended with treated lake water	Cl <sub>2</sub> , UF,UV,NH <sub>3</sub> , Dechlorination, RO, GAC, UV, NH <sub>3</sub> , Cl <sub>2</sub>	n/a	Lahnsteiner et al.,2018	
	El Paso, Texas, USA (2020)	27.3	The goal is blending in the distribution system	MF, NF or RO, AOP	Not started yet	Lahnsteiner et al. (2018)	
Type of use	Name of Recycled water Plant/ Location	Capacity (MLD)	Purpose of Use and Source of water	Treatment Technologies and water quality	Energy Intensity (kWh/kL)	References	Remarks
Indirect Potable Reuse (IPR)	Singapore/NEWater	28.4	Meets 2.5% of the city's potable water for industrial use	RO	Average 0.66 kWh/kL	Lafforgue and Lenouvel (2015); Agelakos and Gikas (2014)	Excluding pumping
	Ground Water Replenishment System (GWRS)/Orange County, California, USA	265	GW recharge and saline water barrier) world's largest. Meet 20% replenish water – the primary source of municipal water supply for of 2 million residents.	Sequential MF, RO, UV and H <sub>2</sub> O <sub>2</sub> treatment. IPR/HQ	0.65–1.22 kWh/kL	Verstraete and Vlaeminck (2011); Navigant Consulting Inc. (2006) Grant et al. (2012)	Excluding pumping
	Belgium/Kokksijde (installed in 2002) Torrelle Wastewater Recycling Plant	8.2	Meets 27% drinking water through GW recharge Raw water: 40% Secondary treated wastewater using CAS/HQ water	UF and RO + dune infiltration	0.75 kWh/kL	Verstraete and Vlaeminck (2011); Van Houtte and Verbauwhede (2008)	Excluding pumping
	Singapore/NEWater (NE Factory)	378	Industrial cooling towers (349 MLD from five reclamation plants). Meet 18% of total water demand and 32% industrial water demand.	MF/UF, RO, and UV HQ water	Average 0.66 kWh/kL	Verstraete and Vlaeminck (2011); Angelakis and Gikas (2014); Grant et al. (2012); Tchobanoglous et al. (2011); Verstraete and Vlaeminck (2011) PUB (2011)	Excluding pumping
Non Potable Reuse (NPR)	Ulu Pandan Reclamation Plant in Singapore (NPR)	23	Commercial and Industrial Use	MBR and RO (more than 20 such projects are ongoing)/ HQ Water	1.7 kWh/kL		Excluding pumping
	Australia/Melbourne/World's largest WSP/Eastern Treatment Plant	330	Non-drinking purposes. Class A recycled water	O <sub>3</sub> and UV disinfection, biological filtration and chlorination-HQ	1.2 kWh/kL	Melbourne Water (2017) Parliament of Australia (2005)	Excluding pumping

(continued on next page)

Table A.3 (continued)

Type of use	Name of Recycled water Plant/ Location	Capacity (MLD)	Purpose of Use and Source of water	Treatment Technologies and water quality	Energy Intensity (kWh/kL)	References	Remarks
Type of use	Name of Recycled water Plant/ Location	Capacity (MLD)	Purpose of Use and Source of water	Treatment Technologies and water quality	Energy Intensity (kWh/kL)	References	Remarks
Non-Potable Reuse (NPR)	The USA/The City of San Diego Reclamation Plant	42	Irrigation, industrial use, and landscaping Class A+ water produced	MF, UF, RO and UV Disinfection/Advanced Oxidation (UV light and H <sub>2</sub> O <sub>2</sub> )/HQ water	0.6 kWh/kL	City of San Diego (2015)	Excluding pumping
	Australia/Caboolture Water Reclamation Plant	10	Water supply to Narangba Industrial Estate, a sports ground, a school and other users' enroute). Water quality is of Drinking water standard –Class A drinking water.	Biological denitrification, pre-ozonation, coagulation/ flocculation, dissolved air flotation/sand filtration, ozonation and biological activated carbon treatment, Granular Activated Carbon.	0.9 kWh/kL AWTP-1.69 kWh/kL	Van Leeuwen et al.,2010; West et al. (2015); Lane et al. (2012); West et al. (2015); Hall et al. (2012) (appendix)	Excluding pumping Multi-barrier protection.
	Israel/Dan Wastewater Treatment and Reclamation Plant	350	Irrigation (73% of Municipal Wastewater) (5% of country's total water use) and 13% of municipal supply. (Largest for irrigation)	Phosphorous removal activated sludge with anoxic and aerobic zones and secondary clarification. SAT (soil treatment technology) used for GW recharge.	n/a	Agelakis and Gikas (2014)	
	Australia/Melbourne/World's largest WSP(Western Treatment Plant)	110	Meet 11% of Municipal water supply incl in-plant uses, irrigation of crops, gardens, golf courses and conservation areas	Lagoon system, combined with UV light and chlorine disinfection Class A water	0.63 kWh/kL (calculated from Cook et al., 2012 and Kenway et al., 2008)	Grant et al. (2012); Melbourne water, 2017; Cook et al. (2012), Kenway et al. (2008)	Excluding pumping
	Northern California	252	Irrigating parks	Activated Sludge, Solid anaerobically digested and dewatered	1.89 kWh/kL	Shehabi et al. (2012)	Excluding pumping
	Western Corridor Water Recycling	232	Non-potable uses	Reverse Osmosis	2.46 kWh/kL	Hall et al. (2009)	Including Pumping
Type of use	Name of Recycled water Plant/ Location	Capacity (MLD)	Purpose of Use and Source of water	Treatment Technologies and water quality	Energy Intensity (kWh/kL)	References	Remarks
Non Potable Reuse (NPR)	Africa/Namibia/Old (GWRP)	7.5	Irrigation of city parks and garden. Meet 8% of the total water demand		n/a	Lafforgue and Lenouvel (2015) (critical Review article)	
	Hypo RWTTP	11.32	EQR/NPR	MBR/HQ	1.3	Pellegrin and Kennear (2012)	Including pumping
	Dundee (Georgia)	11.35	EQR/NPR	MBR/HQ	1.67	Same	Including pumping
	Cauley Creek (Georgia) MBR Plant	18.92	EQR/NPR	MBR/HQ	1.58	same	Including pumping
	Healdsburg (California) MBR Plant	6.06	EQR/NPR	MBR/HQ	1.82	same	Including pumping
	Lott Facility MBR Plant	7.57	EQR/NPR	MBR/HQ	1.6	same	Including pumping
	Bonita Spring MBR Plant	15.52	EQR/NPR	MBR/HQ	1.42	same	Including pumping
	North Pine PRW System <sup>o</sup>	INA	NPR (HQ)	RO	1.69	Hall et al., 2009	Including pumping
	North Coast PRW System <sup>o</sup>	INA	NPR (HQ)	RO	1.94	same	Including pumping
	Noosa PRW System <sup>o</sup>	INA	NPR (HQ)	RO	2.02	same	Including pumping
	Caboolture PRW System <sup>o</sup>	INA	NPR (HQ)	RO	1.69	same	Including pumping
	Toowoomba PRW System <sup>o</sup>	INA	NPR (HQ)	RO	2.22	same	Including pumping
	Hinge Dam 3 PR W System <sup>o</sup>	INA	NPR (HQ)	RO	1.78	same	Including pumping
	Redlands PRW System <sup>o</sup>	INA	NPR (HQ)	RO	1.78	same	Including pumping

INA-Info not available, HQ-High Quality water.

**Table A.4**Intensity of Decentralised Potable<sup>14</sup> and Non-Potable Reuse (Case 3 and Case 4 of Fig. 1 in the Main Text)

Country/Location	Volume (kLD)	Scale and population served	Purpose/Uses	Treatment Technologies and water quality	Energy Intensity (kWh/ kL)	References	Remarks
Australia/Cap De Monte, SEQ	11	Small-scale/community level/46 dwellings and a community centre/ Dual reticulated system (DRWS)	NPR Reticulated/dual system	MBR and H <sub>2</sub> O <sub>2</sub> /UV AOP(AOT)	H <sub>2</sub> O <sub>2</sub> /UV AOT is less energy intensive that uses 0.23 kWh/kL for Cap De Monte case. 5.54 kWh/kL for MBR	Chong et al. (2012)	Includes pumping
Australia/Cap De Monte in Mount Tamborine, SEQ	11	Cluster/community (4.3-ha area, 46 residences and a community centre about 2500 population) No sewerage connection and no Supply Main. Rainwater and Bore are used for potable water supply. (DRWS)	NPR Achieving self- sufficiency dual pipe system for toilet flushing and outdoor uses. High-quality Class (A+)	Activated sludge system with fine screen (2 mm size), anoxic an aeration zone (nitrification and denitrification) and MBR. Advanced treatments used are UV disinfection and sodium hypochlorite chlorination. ** BOD, COD and TN are a higher value than those in centralised WWS.	Energy intensity was 17.1 kW h/kL. This high value was found due to use of oversized chlorine mixing pump (5.5 KW) and due to operation schedule of the pump.# Using a 1.1 kW pump, EI reduced to 11 kW h/ kL Pumping energy 0.5 kWh/kL	Sharma et al. (2012)	Includes pumping
Curumbin Ecovillage/ Australia	51	110 residential lots ranging from 400 to 1600 sq.m area (can increase capacity by 25%) (DRWS)	For toilet-flushing, garden watering, car washing, communal irrigation and firefighting (achieving self-sufficiency)	Anaerobic primary treatment, denitrification and Textile Filtration** microfiltration, UV disinfection, and chlorination.	1.67 kWh/kL Pumping energy 0.51kWhkL	Sharma et al. (2012)	Includes pumping
Country/Location	Volume (kLD)	Scale and population served	Purpose/Uses	Treatment Technologies and water quality	Energy Intensity (kWh/ kL)	References	Remarks
Northern California	54.8	Community scale/47 Lots (septic tanks are connected with 5 km sewer main and then transported to a community treatment plant (Non-Potable Reuse) 100 popn	For irrigation parks	Recirculating sand filter pumped through 0.6 m gravel bed + UV supply sump system for disinfection.	10.3 kWh/kL. Includes pumping and other factors. Treated water is pumped to 11.4 m3 hilltop dosing tank and then distributed by gravity.	Shehabi et al. (2012)	Includes pumping
Australia/Rose Hill	6000 KLD <sup>1</sup> (cover now 20000 <sup>2</sup> residents)	DSRWS. More than 15,000 Properties are connected. One of the most significant residential areas in the world utilizing reclaimed water.	NPR such as garden irrigation, toilet flushing and car washing Aim to reduce the quantity of treated wastewater discharged into the river and parallel reduction of the demand for potable water.	Primary, secondary (MBR) and Tertiary (Chlorination and UV)-solid processing.	1 kWh/kL (Sydney Water)-treatment only	Agelakis and Gikas, 2014; ISF (2013a) Sydney Water Conservation Strategy 2010-2015 Parliamentary Report of Australia 2005	Includes pumping (larger decentralised system/ distributed system)
Australia/Darling Quarter Scheme	116	Building scale/single (DSRWS)	To reduce potable water use in the Main.	Moving Bed Biofilm Reactor (MBBR), membrane bioreactor (MBR) and River Osmosis (RO).	4.5 kWh/kL	ISF 2013; ISF (2013b)	High energy use due technologies/HQ water (include pumping)

**Table A.5**

Scale/Size (MLD) of water recycling systems versus energy intensity (kWh/kL) (EPRI 2002; EPRI and WRF 2013) (data converted from kWh/MGD to kWh/MLD) \*\*: Cooley and Wilkinson, 2012; Eaton 2013; Scales et al., 2015; Kavvada et al., 2016)

Size of Plant (MLD)	Membrane Bioreactor (MBR/)	Activated Sludge (ASP)	Advanced Treatment without Nitrification	Advanced Treatment with Nitrification*	Biological Nutrient Removal (BNR)**	Trickling Filter (TF)*	Biological Activated Carbon (BAC)	Advanced Water Treatment (AWT)
0.38					2.14			
0.61	1.82							
0.76					2.13			
4		0.6	0.7	0.8		0.48		
4.16					1.3			
7.57	1.6							
8							0.58	
8.7					0.79			
9.5					1.06			
11.35	1.74							
11.73					0.58			
15.52	1.42							
18							0.56	
18.92	1.58							
20		0.37	0.42	0.51		0.26		
25								0.87
25.74					0.55			
60	0.9							
40		0.32	0.36	0.48		0.23		
75		0.3	0.34	0.43		0.2		0.8
126							0.15	
200		0.3	0.32	0.42		0.2		
322					0.54			
380		0.28	0.31	0.42		0.18		

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